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UTILIZATION OF BIOMASS TO DRY WHOLE CORN

Prepared for

MONTANA DEPARTMENT of NATURAL RESOURCES and CONSERVATION

UTILIZATION OF BIOMASS TO DRY WHOLE CORN

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ABSTRACT

Alternative sources of low-grade energy are becoming more important as the costs of energy from nonrenewable resources rise. Agricultural biomass is a nonrenewable source of low-grade energy that could be used as a heat source, replacing propane fuel for crop drying and space heating. Fuel oil, electricity, and natural gas usage could also be reduced by supplemental heating with biomass-fired heat units.

A project supported by the Montana Department of Natural Resources and Conservation was undertaken by the Southern Agricultural Research Center (SARC) and the Department of Agricultural Engineering at Montana State University to investigate the feasibility of using agricultural residue from crops raised in Montana to dry perishable grains. The project consisted of construction and testing of a commercially available biomass-fired corn dryer.

A direct-fired incinerator-type biomass furnace was constructed, operated, and performance evaluated to determine overall heat conversion efficiency and economics of operation. A computer-aided simulation model of the biomass burner was developed to help determine performance of the burner at conditions other than those tested. Design and operation recommendations were made based upon actual system operation and output from the simulation model of the burner.

CHAPTER 1

BACKGROUND INFORMATION

Introduction

Purpose

The purpose of the research was to lessen the State's reliance on fossil fuels pursuant to the Title 90, Chapter 4, Part 1, MCA and the administrative rules adopted thereunder which states "The purposes of this part are to stimulate research, development, and demonstration of energy conservation and of energy sources which are harmonious with ecological stability by virtue of being renewable, thereby to lessen that reliance on nonrenewable energy sources which conflicts with the goal of long-range ecological stability and to provide for the funding and administration of such research. Furthermore it is the purpose of this part to stimulate the commercialization of alternative renewable energy and to allow the department to make loans through financial institutions in Montana for this purpose."

Scope

The scope of the project was to investigate, design, construct, and demonstrate a biomass combustion furnace fired by agricultural wastes for the purpose of drying high moisture corn. The technologies reviewed included gasification, fluidized bed, and direct combustion. The combustor was to produce a heat output of 800,000 to 1,500,000 BTU/hr.

Objectives

The first objective of this thesis was to outline the design and construction procedures for the biomass-fired grain drying system constructed at the Southern Agricultural Research Center located at Huntley, Montana. Secondly, the performance of the system was evaluated based upon data collected during tests run in November, 1983 and March, 1984. Thirdly, a computer model was developed to simulate the burner performance for the purpose of predicting system behavior to changes in input variables. Fourthly, the discussion section was included, giving the author's views of system performance based upon observations while operating the system and information published on similar research.

English units were used throughout this paper because this is standard industrial terminology in grain drying and handling equipment. There are several references to moisture content throughout this paper. The references were abbreviated as mc and refer to moisture content calculated on the wet basis unless otherwise noted.

Related Research

Gasifier Systems

A gasifier is a two-stage burner. The first stage gasifies the feedstock by using a limited air supply to drive off the volatiles, primarily carbon monoxide. The gas is channelled into a secondary combustion chamber where combustion is completed by introducing more air into the system. The feedstock is gasified in a fixed bed, ashes are removed through a grate at the bottom of the bed, and biomass settles into the gasification zone replacing that which was consumed.

The Agricultural Engineering Department at the University of California, Davis has devoted several years to the development of a downdraft gasifier using walnut shells and other biomass residues for feedstocks. In a downdraft gasifier, the air for gasification is pulled down through the unburned material and the gas is usually extracted from the area underneath the grate. The biomass fuel flows in the same direction as the air. A full-scale portable pilot plant was mounted on a semi-trailer and moved from place to place for demonstration purposes. Numerous publications related to this ongoing research effort are available (Goss, 1977; Goss, et al., 1979; Goss and Williams, 1977; Horsefield and Williams, 1976; Williams and Goss, 1979; Williams, et al., 1977). Current work at UC Davis centers on developing combustion systems and combustion management techniques to minimize objectionable gasifier emissions.

The Agricultural Engineering Department at Purdue University has developed a downdraft gasifier using corn cobs as the main feedstock (Richey, et al., 1980; Richey, et al., 1981; Foster, et al., 1982; Jacko, et al., 1982). Corn cobs, having a relatively uniform size, shape and density, were found to work well as a feedstock in this gasifier.

The Agricultural Engineering Department at the University of Kentucky has worked with biomass combustion using corn cobs, stalks and grain from corn as feedstock for an updraft gasifier (Payne, et al., 1979). The air for an updraft gasifier enters from underneath the grate, while the gas from gasification is discharged through at least some of the feedstock. In this type of gasifier the air and fuel flow

are countercurrent. This aids in drying the feedstock before it reaches the gasification zone. Corn cobs were found to be the most desirable feedstock of the three types mentioned for this particular design.

Direct-Fired Systems

A direct-fired biomass burner works on the same principles as an incinerator. All combustion takes place in one chamber and the biomass is fed into the combustion zone upon demand. The burn chambers are designed to be larger than those in gasifiers to allow complete combustion before the exhaust exits the burner. Larger chambers also help accommodate volatile materials such as straw and corn stover.

The Agricultural Engineering Department at Washington State University has built and tested a direct-fired burner using baled hop residue as the feedstock (Ebeling, et al., 1982). Continuous feeding was accomplished by using a hydraulic ram to slice off a portion of the bale and inject it into the furnace. Problems were encountered in getting efficient combustion because of the compacted nature of the feedstock. A concentric vortex air flow pattern in the firebox was utilized in this unit to help remove particles from the exhaust stream.

The Agricultural Engineering Department at Iowa State University developed an incinerator-type biomass burner that uses unprocessed biomass (straw, corn stalks, or similar material) as the feedstock (Sukup and Bern, 1982). A standard 9-inch screw conveyor was used for continuous feeding of the feedstock. A large burn chamber design made it possible to burn volatile material in this unit. The particulate emission rate was comparatively equal to or less than two gasifier units which were tested at the same time (Barrett, et al., 1981). Versions of

the unit are being built commercially at the Sukup Manufacturing Company in Sheffield, Iowa.

Work has been done on cord wood gasification in the Department of Agricultural Engineering at Clemson University (Payne, et al., 1981). Cord wood is usually batch-loaded into the gasifier. This feeding system increased labor requirements in operating the system. It was not possible to top load the hot gasifier on a continuous basis, and efficiency was reduced as the diameter of the cord wood feedstock increased.

Montana Based Fuel Sources

Cord Wood

Some Montana residents use cord wood as an alternative fuel for residential space heating. A great quantity of fuelwood is not readily available in many of Montana's crop growing areas. As a result, a cord wood combustion system was not considered for the research and development effort being reported.

Cereal Straw

The following cropland acreages are utilized for production of the four major grains in Montana and are expressed in millions of acres (Pratt, 1982).

wheat	-	5.82
oats	-	0.11
barley	-	1.32
corn	-	0.08

Cereal straw was the after-harvest residue from 98-99% of cropland in Montana that was planted into the four major crops. Unprocessed

straw has a tendency to bridge which could cause problems in a fixed-bed gasifier. Unprocessed straw has a very low bulk density. Most straw contains about 6-7% ash; approximately half of which is silica (Staniforth, 1979). Silica tends to fuse into a slag at temperatures above 1,200 ^{O}F. Fused ash can affect gasifier performance by restricting the air and fuel flow, and makes it difficult for the ash to fall through a grate. Wheat and barley straw have typical heat contents of 7570-7750 BTU/lb dry matter and typical moisture contents at harvest time of 9-13%.

Corn Cobs And Stover

The material referred to as stover in this paper is defined as the stalks, leaves, and husks of the corn plant. Corn stover burns in a manner similar to cereal straws. It is highly volatile, and has similar heat value and density. The corn cobs and stover can be collected with a combine-mounted attachment that blows the stover and cobs into a wagon, or by using a flail chopper. Corn cobs are dense as compared to stover or straw. Corn cobs have an average ash content of 1.6% and a gross heat of combustion of 8023 BTU/lb (Payne, et al., 1980). Corn cobs have been collected separate from the stover. One possible method is to open the combine sieves allowing both the corn and the cobs to discharge into the grain tank. The cobs could then be separated from the corn at the grain storage facility. It is simpler to collect all of the cobs and stover that are discharged from the combine.

Wood Chips

Wood chips are available in some locations in Montana, especially around concentrated areas of the timber industry. They are of small and uniform size, but may tend to bridge in some feeding mechanisms. The bulk density of wood chips is low, requiring large feeder storage volume. Wood chips would be a satisfactory feedstock for burner systems installed close to the fuel source.

CHAPTER 2

SYSTEM DESIGN

Selection Criteria

Furnace Selection Criteria

A biomass furnace, for use in Montana, must be able to use cereal straw as a main feedstock. It should also accommodate other secondarily available agricultural biomass fuels such as corn stover, hay, and wood chips.

Consideration of the combustion characteristics of the available fuels indicated that an incinerator-type, direct-fired biomass furnace would be the most successful in terms of fuel use efficiency, day-to-day operation and management. Unprocessed straw and corn stover could be fed into this type of unit, eliminating the problem and expense of processing the feedstock into the uniform size and density necessary for gasification. Usual practices associated with collection and storage such as piling or baling were acceptable. To avoid excessive labor costs, the prototype system specifications included semi-automatic operation.

Selection Of Commercially Available Biomass Burner Unit

A decision was made to purchase a commercially available biomass burner for the following reasons:

1. The time frame for the project completion did not allow adequate time for design and construction of a furnace.

2. Past research could be most efficiently utilized with the purchase of a ´field-proven´ burner.

3. A burner on the market could easily be adapted to burning Montana-based fuels.

There were three units readily available on the market with the required combustion rate of 800,000-1,500,000 BTU/hr.

Stormor Manufacturing Company built an incinerator-type burner that used large round bales as the feedstock. The bales were loaded whole and burned in batches. Problems were anticipated in getting the bales to burn at a constant combustion rate. Difficulty in controlling the output temperature, emissions, and combustion rates were also anticipated. A possible solution would be to use a propane burner as a supplemental heat source in series with the furnace to maintain a constant drying air temperature.

Clayton and Lambert Manufacturing Company manufactured an updraft gasifier that was designed to use corn cobs as the feedstock. Primary Montana fuels (straw, hay and stover) could not be burned in this unit without prior processing. An adequate supply of corn cobs is normally available from the harvest of a corn crop to supply the fuel necessary to dry the corn produced, but other sources of biomass are necessary if the heat unit is used for purposed other than corn drying.

Sukup Manufacturing Company built a direct-fired burner than could utilize unprocessed biomass (straw, corn cobs and stover) as a feedstock. This unit was developed at Iowa State University and subsequent improvements were made by the manufacturer.

The direct-fired incinerator type biomass burner, manufactured by Sukup Manufacturing Company, Sheffield, Iowa was selected for this application for the following reasons:

1. The unit had an output range of 310,000 to 1,930,000 BTU/hr (Sukup and Bern, 1982).

2. The unit had been on the market for a few years and was field proven.

3. Automatic controls were supplied.

4. It had the capability of burning unprocessed cereal straw with no apparent further modification.

5. It could accommodate other secondary feedstocks, including corn cobs and stover.

6. It did not utilize a combustion grate that could be plugged by slag-forming high-silica ash.

7. One of the feeding systems utilized a feed wagon that was already available on the experiment farm.

8. A heat exchanger could easily be adapted to the system with little modification of the unit.

9. The unit was immediately available, and reasonably priced.

Biomass Feed System Selection Criteria

The biomass feeding system was selected to be compatible with the material to be handled and the burner it fed. Two systems were readily available for this purpose. One system used a 10 ft x 16 ft stack feeder to tear apart large round bales and loose biomass material. The alternative was a 4 RPM gearmotor electric drive unit that adapted to the PTO shaft of a John Deere chuck wagon for feeding chopped straw or corn cobs and stover.

The feeding system was designed to deliver enough biomass to the burner to maintain the desired burner output. It had an automatic

control system to turn the feeding system on and off as biomass was demanded by the furnace. Either baled or loose biomass could be handled by the stack feeder.

The biomass feed rate was calculated as follows:

$$M_b = Q/(q \times e) \tag{2.1}$$

where:

e = overall thermal efficiency of heat unit

M_b = biomass mass flow rate in lbs/hr

Q = maximum heat output of burner in BTU/hr

q = net heat content of biomass in BTU/lb

Using Q = 1,800,000 BTU/hr, q = 4300 BTU/lb, and e = .75 yields M_b = 698 lb/hr for the calculated maximum biomass feed rate.

Drying System Criteria

Figure 1 is a schematic illustration of the biomass-fired grain drying system constructed at Huntley. The grain drying system was designed to match the burner specified above. Specifications also included completely drying a batch in one working day to eliminate the need for night operation or reheating the corn to drying temperatures. A start-up time of one-half to one hour, necessary to produce clean exhaust, was included in the calculation of the drying time.

The design value for the temperature of the drying air was chosen to be between 120 °F and 160 °F for effective drying. Temperatures higher than 160 °F could damage the grain. Temperatures lower than 120 °F result in an excessively long drying time, increasing the labor requirements and reducing system capacity.

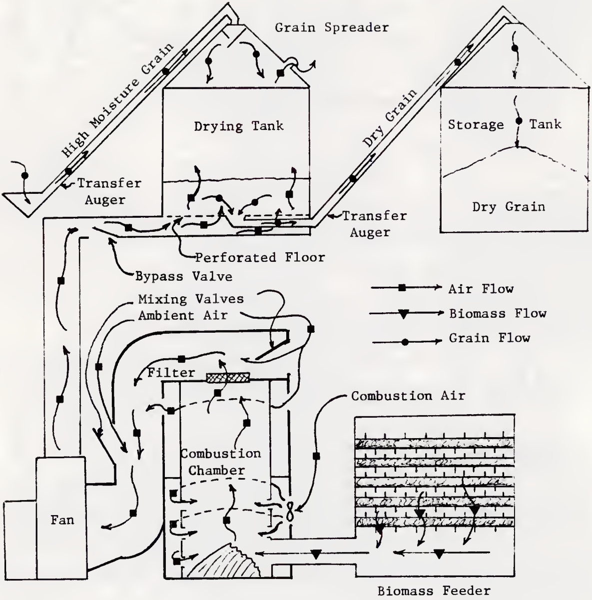

Figure 1. Grain drying system schematic illustration.

Air Handling System Design

Drying Air Temperature Rise

The difference in temperatures between the drying air and the ambient air was calculated, assuming a standard ambient air temperature of 60 ^{o}F and a minimum desired drying air temperature of 120 ^{o}F. Substituting these values in Equation 2.2 results in a temperature rise of 60 ^{o}F.

$$T_o = T_2 - T_1 \qquad (2.2)$$

where:

T_o = temperature rise, ^{o}F

T_1 = ambient air temperature, ^{o}F

T_2 = drying air temperature, ^{o}F

Air Flow Rate And Pressure Drop

The air flow rate of the fan, calculated using Equation 2.3, was selected to match the desired temperature rise and the heat output of the biomass heat unit.

$$M_a = Q/(C_p T_o r K) \qquad (2.3)$$

where previously undefined variables are as follows:

C_p = air specific heat, BTU/lb dry air

K = constant = 60 min/hr

M_a = air flow rate, cfm

Q = average heat output of the heat unit, BTU/hr

r = air density, lbs/ft^3

Using Q = 1,000,000 BTU/hr, C_p = .241 BTU/lb ^oF, r = .071 lb/ft^3 @ 100 ^oF and pressure of 29.92 inches of mercury and T_o = 60 ^oF yields M_a = 16,234 cfm.

Figure 2 in ASAE D272.1 (Baxter, 1982) is a design aid for determining the pressure drop through a layer of grain. It requires the use of the airflow rate in units of cfm/ft^2 of perforated floor area in the drying tank. The type of grain being dried was also needed to find the pressure drop. The airflow rate per unit area was calculated as follows:

$$M_a' = M_a/A \tag{2.4}$$

where previously undefined variables are:

A = area of perforated floor, ft^2

M_a' = airflow rate, cfm/ft^2 of floor area

Using M_a = 16,500 cfm and A = 303.9 ft^2 yields M_a' = 54.29 cfm/ft^2.

From ASAE D272.1, the pressure drop is 0.8 inches of water per foot of shelled corn for the conditions noted above. Calculation of the pressure drop yields:

$$P = p \times d \times F \tag{2.5}$$

where previously undefined variables are:

d = grain depth, ft

F = factor to account for compaction, fine materials and perforated flooring, F = 1.5 for the conditions noted

p = pressure drop per foot of grain, inches of water

P = total pressure drop through layer, inches of water

Using $p = 0.8$ in/ft of grain and $d = 4$ ft of grain yields a P of 4.8 inches of water.

The calculated pressure drop did not equal the initial pressure drop assumption, so the calculations were reworked with a new assumption. Assuming $P = 4.5$ inches of water and reworking yielded $P = 4.6$ inches of water with a fan output of 16,000 cfm.

Literature on commercially available fans, indicated that a 27-inch diameter centrifugal wheel turning at 1750 RPM would deliver 16,500 cfm at 4 inches of static pressure and require 19.3 horsepower. These fan specifications were used.

Drying Tank Design

Bin size selection was achieved by obtaining a suitable volume of corn to fully utilize the heat generation capacity of the burner while maintaining a corn depth suitable for effective drying. The calculations below were performed using several standard bin diameters. A tank diameter of 19.67 ft was selected as the smallest feasible for this system. A larger tank could have been utilized if the purchase price was justified. A 1000 bu/hr automatic unloading system, and a 1000 bu/hr grain spreader were specified for effective handling of the grain.

Area Of Perforated Floor

A 12-inch air plemum beneath a perforated drying floor was specified. The area of the perforated floor was calculated using the formula for determining the area of a circle.

$$A = 3.14 \times D^2/4 \tag{2.6}$$

where:

A = area of perforated floor, ft^2

D = drying tank diameter, ft

Using $D = 19.67$ ft yields $A = 303.9\ ft^2$.

Batch Volume

For thin-layer batch drying the grain depth should be between 2-4 ft (Brooker, et al., 1974). Less than 2 ft would result in inefficient use of available burner heat and greater than 4 ft would cause overdrying, less airflow due to increased pressure drop, and/or heat stress to the bottom layer of grain before the top layer is completely dry. Batch volume was calculated by:

$$B = A \times d \times K' \qquad (2.7)$$

where previously undefined variables are as follows:

B = batch volume, bu

d = grain depth, ft

K' = constant = 0.8 bu/ft^3

Using the maximum recommended depth of $d = 4$ ft, and $A = 303.9\ ft^2$ yields $B = 972.5$ bushels.

Drying Time

Drying time was estimated as follows. The required amount of water to be removed from the batch of wet corn was determined. That value was multiplied by the estimated drying efficiency and then divided by the estimated burner output.

The weight of a bushel of wet corn was determined using Equation 2.8.

$$WB = DB \times (\%dm\ of\ DB)/(\%dm\ of\ WB) \tag{2.8}$$

where:

DB = weight of a dried bushel of corn, lbs

WB = weight of a wet bushel of corn, lbs

% dm = percent of dry matter in a bushel of corn

Assumptions used in the calculations were as follows: Corn initially at 25% mc was to be dried to 15.5% mc. A bushel of 15.5% mc corn weighed 56 lbs. This yielded WB = 63.09 lbs/bu of 25% mc corn.

The weight of water per batch of corn was determined as follows:

$$w = (WB - DB) \times B \tag{2.9}$$

where previously undefined variables are as follows:

w = water removed from a batch of corn, lbs

B = batch volume, bu

Using WB = 63.09 lbs, DB = 56 lbs and a batch size of 972.5 bu yields w = 6895 lbs of water to be removed from the batch of grain.

The drying time was calculated using Equation 2.10.

$$t = (E \times w)/Q \tag{2.10}$$

where previously undefined variables are:

t = drying time for a batch of wet corn, hrs

E = estimated efficiency of the dryer system, BTU/lb of water removed

Q = burner output, BTU/hr

Using E = 2,000 BTU/lb of water, w = 6,895 lbs of water removed and maximum burner output of Q = 1,800,000 BTU/hr yields t = 7.6 hrs drying time. This allowed 2.4 hrs for system start-up, shut-down and cleanup in a 10 hr day.

Additional Equipment For Grain Handling And Storage

A storage tank of the same diameter as the drying tank was specified to make it possible to purchase one unload auger and one sweep auger for use in both tanks. An adequate flush-floor aeration system was installed in the storage tank to facilitate conditioning of the grain. Center unload tubes were installed to protect the bins from uneven side loading during grain transfer operations.

CHAPTER 3

SYSTEM CONSTRUCTION

Construction on the project began in June of 1983 and was completed in October of 1983. Most of the work was done by the author and employees of the Southern Agricultural Research Center. Specialized work such as concrete, backhoe work, and electrical wiring was subcontracted because of the lack of equipment and tools. Time, cost, and quality of work were major considerations in selecting the best means of construction of each stage of the project.

Site Selection And Preparation

The site was selected to give adequate room to build the existing facility and for expansion in the future. It was necessary to plan the facility to accommodate semi-tractor and trailer vehicle access. Location of electricity, soil conditions, overhead power lines, and site work were other considerations in the final site selection.

A backhoe and operator were hired to remove old foundations prior to site preparation for the new facility. Figure 2 shows the removal of unwanted material from the site. Gravel was hauled in from a pit located on the farm to raise the facility above the present grade. This was needed to keep runoff water levels below the unload tubes.

Figure 2. Site preparation for grain bin foundations.

Biomass Burner Unit Assembly

The biomass burner unit was assembled at the same time that the site work was being done. This was possible because the unit was mounted on a portable trailer. The burner was assembled near the farm shop, simplifying the construction process. Figure 3 shows the biomass burner completely assembled and mounted on a trailer. Also shown are the automatic control panel, discharge air duct, auxiliary combustion air fan, and small feed hopper.

A heat-protective firebrick liner was stacked inside the burner according to specifications supplied by the manufacturer. A filter was installed in the top of the burner. It consisted of a firebrick holder with a layer of steel balls as illustrated in Figure 4. The filter was installed after the burner was in place to reduce filter damage.

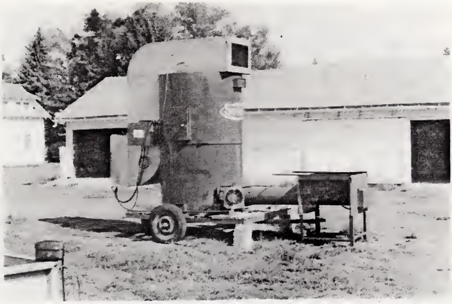

Figure 3. Biomass burner unit placed on portable trailer.

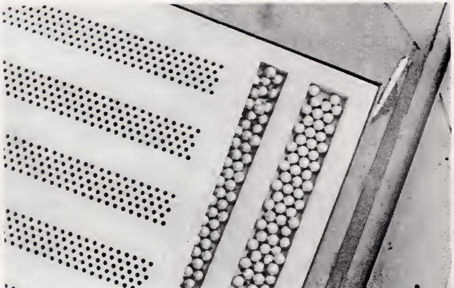

Figure 4. Exhaust gas filter with ball bearing filter media.

Concrete Work

The placing of concrete for the bin foundations began once site work was complete. An aeration tunnel was formed and the unload tube placed in the storage tank foundation at the same time the concrete was placed.

Steel Erection

The galvanized grain tanks and accessories were installed according to the erection manuals supplied by the manufacturer. The drying tank was erected first. The accessories (drying floor, unload tube, air transition, etc.) for the drying tank were installed as the storage tank was being built.

Electrical System

The first step in electrical system planning was to contact the power company. The engineer from the power company visited the site and all of the possibilities were evaluated before making a decision on what source of electrical power to use. Costs of new installations, capacity of existing facilities, and operation and maintenance costs were some of the factors considered in selecting the most appropriate power supply.

All motors purchased for the system were 3-phase 440-volt, based on consideration of price, motor life, and maintenance. A phase converter was installed to convert available 1-phase 440-volt power to 3-phase 440-volt power. A magnetic starter was installed for each motor for overload protection, operator safety, and system automation. It was necessary to install a dry transformer to obtain 110-volt 1-phase power from the incoming 440-volt 1-phase power.

CHAPTER 4

SYSTEM OPERATION

Overview Of Burner Operation

The heat unit burned biomass such as straw or a blend of corn cobs and stover, which produced a high temperature exhaust that was blended with ambient air and then channeled directly into the drying chamber at temperatures between 120 ^{o}F and 160 ^{o}F. The amount of fuel fed into the burner was controlled by a thermostat which was set to the desired burner exit air temperature, the average range being 1000 ^{o}F - 1500 ^{o}F. The thermostat was set manually by an operator who adjusted it to obtain the desired thermometer reading in the drying plenum (120 ^{o}F - 160 ^{o}F). The drying air temperature can be controlled either by changing the thermostat setting of the furnace exit air temperature or by adjusting the ambient air blending valves. Usually the system would come into equilibrium within an hour of start-up. The drying air fluctuated within five degrees of the desired temperature indicating that the fuel was burning at a fairly steady rate. The 5 ^{o}F fluctuation occurred because the biomass feeder was either on or off, not a truly ′steady state′ feed system.

Material Flow Of Biomass

This section describes the flow of materials in the biomass collection and handling system utilized at the Southern Agricultural Research Center during the fall of 1983.

A combine attachment was used to collect the biomass material that was discharged from the sieves and straw walkers on a three-row harvester. A wagon was pulled behind the combine to collect the stover, at a distance necessary for travel clearance when turning corners. Constant adjustments were necessary on the blower discharge deflector shield to keep the biomass material from missing the wagon.

A 30-hp tractor was used to pull the full wagons from the field. The wagons were emptied by means of a drag chain located in the bottom of the wagon. The drag chains were driven by a drive shaft connected to the tractor PTO. The wagon was then pulled back to the field and exchanged with the full wagon behind the combine. One tractor and operator was all that was necessary to keep up with the combine if the biomass was stored at the end of the field.

Appendix I summarizes typical harvest time requirements and the extra time required to harvest the stover. Field capacity is reduced to approximately 87% of normal when stover is collected.

Appendix II contains biomass production figures for the season. The corn/biomass yield ratio for the fields harvested was approximately:

$$\frac{\text{7,290 lb corn (19\% mc, wb)}}{\text{2,400 lb stover (33\% mc, wb)}} = \text{approximately 3:1 corn:stover ratio on an oven-dry basis}$$

Approximately one-quarter of the biomass that was collected from the fields was used to dry the corn. The biomass was moved from the storage piles to the feeder unit with a loader tractor equipped with a grapple fork. The tractor was weighed on a truck scale, loaded and then again empty, to determine the weight of the biomass used during a test.

The remaining three-quarters of the biomass was used in the feedlot as bedding. It was placed in the pens using the same method outlined above for the feeder.

The furnace feeder had a drag chain that moved the biomass towards a set of beaters as shown in Figure 5. The beaters tore biomass from the pile and discharged it into a hopper. A 9-inch auger approximately 15 ft long moved the biomass material from the hopper bottom into the base of the burner. The biomass was ignited inside of the burner, producing heat, carbon dioxide, water and ash.

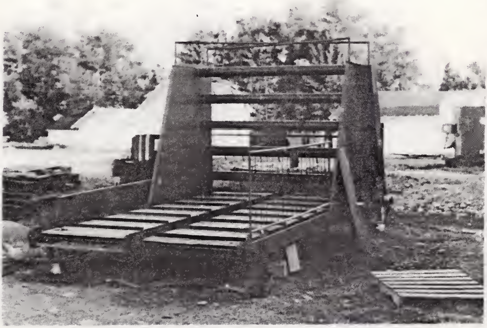

Figure 5. Biomass furnace feeder unit.

The ash was periodically removed from the system manually with an ash rake supplied with the burner. An ash door located at the bottom of the burner supplied access for cleaning purposes.

The biomass material flow system is illustrated schematically in Figure 6.

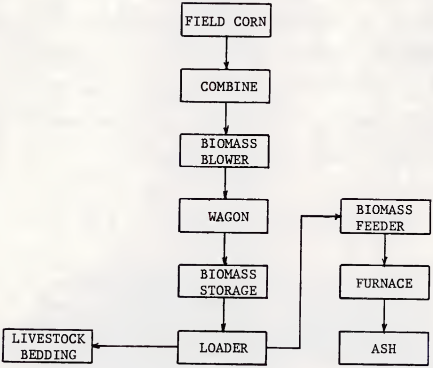

Figure 6. Biomass material flow diagram.

Grain Corn Material Flow

Corn was planted on thirty-five acres at Huntley, yielding 4,252 bu, for an average production of 121.5 bu/ac (Appendix III). This was an overall average from nine different varieties that were planted on the station for experimental purposes. The corn was removed from the cobs in the combine and discharged into the holding tank. The holding tank would hold approximately 60 bu of shelled corn. In most cases a full round could not be made on a quarter mile long field. A truck was located at either end of the field where the combine holding tank was

emptied. To save time, the biomass wagons were usually exchanged at the same time whether they were full or not.

The trucks were driven from the field by a third operator. The trucks were weighed on a truck scale and then emptied into the hopper of an auger at the bins. High soil moisture discouraged moving loaded grain trucks through the fields.

A 42-ft long, 7-inch diameter auger was used to convey the corn to the top of either the drying tank or a wet holding bin. It was geared down from its maximum capacity of 2,300 bu/hr so that it would not exceed 1000 bu/hr, matching the capacity of the grain spreader.

The grain spreader, located within the top access hatch of the drying tank, was used to spread the grain in the tank. This limited the amount of shovelling necessary for a level batch to 5-10 minutes. Once the corn was dried and cooled, it was removed from the drying tank using a 6-inch automatic sweep auger at approximately 700 to 1000 bu/hr. The sweep discharged the corn into a center unload tube.

The grain was conveyed from the center to outside of the tank with a 5-inch screw conveyor inside a 6-inch center unload tube. The flow could be controlled by a slide gate at the auger inlet, if necessary. An auxiliary slide gate is located near the door to remove the grain from next to the door, eliminating excess weight on the sweep auger in order to start it, and providing access for a person to the tank.

The corn emptied into the hopper of the 42 ft auger, which had been moved from the tank loading position. The corn was conveyed to the top of the storage tank and discharged into the tank.

The corn material flow described above is illustrated in Figure 7.

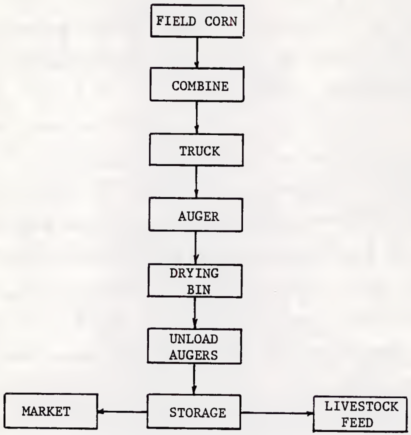

Figure 7. Corn material flow schematic.

Air Flow

The function of the biomass burner was to heat ambient air to at least 120 ^{O}F. A description of the air movement through the system and the conditions of the air at different points in the system follows.

Ambient air conditions varied from day to day. Fall temperatures at Huntley, Montana in 1983 ranged from -10 ^{O}F to 80 ^{O}F. Relative humidities ranged from 15% to 90%. The condition of the air at the inlets of the burner and the blending valves was determined by the ambient air conditions.

The portion of the drying air channelled through the burner was heated to temperatures between 1000 ^{o}F and 1600 ^{o}F. The combustion process and evaporation of moisture in the biomass fuel added water to the air inside the burner.

Some of the drying air was channelled through a 6-inch chamber surrounding the top half of the burn chamber. This air cooled the burner and reclaimed some of the heat transferred through the walls of the burner.

The remainder of the drying air was introduced at ambient temperature through the two blending valves located on the air duct between the burner and the drying fan as shown in Figure 1. The valves were adjustable, providing one means of control of the drying air temperature.

Air movement through the burner, the surrounding chamber, and the blending valves was induced by the suction of a 20-hp centrifugal drying fan. The fan discharged the drying air into the plenum of the drying bin.

A bypass valve was used to turn the air into the atmosphere during start-up and shut-down. Any smoke in the air due to inefficient burning of the biomass at cooler temperatures would then be bypassed from the batch of corn. The drying air was turned into the drying bin by closing the bypass valve when smoke could no longer be visually detected in the air stream. The temperature of the drying air in the drying plenum was between 120 ^{o}F and 160 ^{o}F.

The air passed through a galvanized steel perforated drying floor into the layer of wet corn. Heat was initially lost to the corn to

warm the corn to drying air temperatures. Moisture was evaporated from the corn adiabatically until the air was either saturated or discharged from the top of the corn layer.

Air temperature dropped due to heat loss to the corn and/or adiabatic evaporation of the corn moisture. Typical exit air temperatures were between 50 ^{o}F and 70 ^{o}F. The cool moist air was then discharged back into the environment through the hooded roof vents or the bin access hatches.

Fuel Considerations

Biomass Fuel Heating Value

The biomass heating value was determined by performing a bomb calorimeter test on a blend of corn cobs and stover. The blend was estimated to be 50% corn cobs and 50% stover on a dry matter basis. Net heat content was determined to be 4078.63 Calories/gram (7342 BTU/lb) of dry matter. The biomass used as fuel was collected from the field at an average of 33% mc (Appendix IV). Its average net heating value was:

$$7342 \text{ BTU/lb} \times (1-.33) = 4919 \text{ BTU/lb biomass} \qquad (4.1)$$

Biomass Fuel Use Rate

Data from three furnace runs performed in March of 1984 was collected and the results were evaluated for specific fuel consumption. Table 1 is a summary of the biomass fuel used to heat the drying air. The burner was ignited using a propane torch to help eliminate emissions during warmup and reduce start-up time. Propane had an approximate

heating value of 21,900 BTU/lb. A total of 1908 bu of corn were dried in the three batches, equivalent to 13.6 ac of corn at 140 bu/ac.

Table 1. Biomass fuel usage in three furnace runs for drying corn.

BATCH #	STARTUP PROPANE (LBS)	STARTUP BIOMASS (LBS)	RUN BIOMASS (LBS)	BTU/AC $(x10^{-6})$
1	1.50	205	1025	1.62
2	3.75	185	975	1.43
3	2.25	150	1435	1.74
TOTALS	7.50	540	3435	1.60

The biomass that was used for start-up was measured separately from the biomass used during the run time to help determine the amount of biomass needed for start-up procedures. The BTU equivalency of the biomass was calculated based on dry matter content of the fuel, assuming a heat content of 7342 BTU/lb dry matter. Using an overall fuel use efficiency of 68.4% for biomass (as determined by averaging overall total efficiencies from the performance data in Appendix V) and an assumed overall fuel use efficiency of 80% using propane, the equivalent BTU usage for propane would be 1.37×10^6 BTU/ac.

Electrical Power Requirements

Table 2 shows the electrical power required to run the drying system. The electrical power requirements were calculated using nameplate horsepower ratings and were verified with a watt meter. Adjustments were made because the fan was drawing more electrical power than its rated 20 hp and the feeder motors did not run continuously. The extra electrical power usage of the fan was due to motor efficiency.

Table 2. Electrical power requirements.

OPERATION	TIME (HR)/BATCH	KW	3 BATCH KWH
LOAD BIN	1	6.0	18
DRY GRAIN	8.6	22.2	573
UNLOAD BIN	1	6.8	20
		TOTAL	611

System Performance and Data Collection Methods

Biomass Moisture Content

Moisture content was determined for representative samples of the cob and stover biomass mixture. Gunny sacks were filled with the biomass material taken from the feeder unit on the days of the tests. Oven-dry sample weight was determined at the end of the time period for the corn cobs and stover and compared to the initial sample weight. Moisture content was calculated from the resulting data. Appendix IV contains summary data and calculations for the corn and stover moisture contents. The corn cobs and stover was determined to be approximately 33% mc at harvest time. Due to the wide range of results and low number of samples, statistical accuracy of the results was not determined.

Corn Moisture Content

Corn moisture samples were taken by two different methods. The first method involved taking samples as the corn flowed out of the tailgate of the truck at harvest time. The second method used was probing the layer of corn in the drying bin. The moisture content was determined by the method outlined in ASAE Standard S352 (Baxter, 1982).

Appendix VI contains the data collected for determining moisture contents of the corn. The moisture content data for March of 1984 was taken in the following manner. A batch of corn was loaded into the drying bin. The corn was levelled and then probed at four locations. The grain probe was sectioned into compartments, allowing isolated samples to be taken at different depths of the batch of corn. Samples were taken from layers approximately 6 inches deep within the batch of corn.

The samples were labelled with a number such as 1W23. For this sample number, 1 represents the batch number, W signifies that the sample was taken before the drying cycle, 2 represents which of the four probings the sample was taken, and 3 means the sample was the third one down from the top of the grain.

The first and second probing were always closest to the fan transition, the point that air enters the drying plenum. Probings 3 and 4 were taken parallel to 1 and 2, further away from the transition. The samples were taken this way to check the uniformity of the airflow through the batch of grain. The air flow was uniform based on the average moisture contents of the probe samples. Variance was probably due to varying depths in a batch of corn rather than restrictions under the drying floor.

The right hand column of the tables in Appendix VI is the average moisture content of the grain per probing. The moisture content of a batch was taken to be an average of the four moisture contents determined by the probing method. This method was chosen to try to eliminate error due to uneven grain sample weights.

Biomass Burner Heat Unit

The biomass burner unit heat output was calculated by measuring the wet and dry bulb temperatures of the furnace entrance and exit air streams to determine their respective enthalpies. The difference in enthalpies was used as a measure of heat added to the air.

The heat input was calculated by taking the average fuel feed rate and multiplying it by the net heating value of the biomass. The ambient air temperature and heat unit exit air temperature were monitored continuously. A 24-pt copper-constantan thermocouple recorder was used to monitor the temperatures. Three thermocouples were used in both locations in an effort to eliminate erroneous data. Potential error sources included the effects of solar radiation, wind, and heat from the burner unit. These errors were minimized by selective placement of the thermocouples.

The relative humidity of the ambient air was measured once for each test with a sling psychrometer to determine the humidity ratio of the air. The humidity ratio was assumed to remain constant throughout the time required to dry each batch. The humidity ratio of the burner exit air was calculated by the summation of the ambient air humidity ratio, water added due to the fuel moisture content, and water added due to the combustion process. It was assumed that all of the moisture due to the combustion process and fuel moisture was channelled into the drying plenum. The fuel feed rate was assumed to be constant throughout the run, although it varied slightly with variations in fuel moisture content.

Appendix V is a summary of the ambient and drying air temperature data taken in March of 1984. Also included are the results of the calculations to determine air enthalpies, moisture contents, and amount of heat added to the drying air by the burner.

Burner efficiency was calculated using only data from the drying cycle while the burner was operating at steady state conditions. The overall efficiency was calculated with consideration given to both the amount of fuel used during start-up and the heat reclaimed during the cooling cycle, or the ratio of the total fuel used during a batch and the total amount of heat added to the drying air. In either case, efficiency was assumed to be (heat in)/(heat out). The results of the three runs performed in March of 1984 are outlined in Table 3.

Table 3. Biomass furnace batch operation information, March 1984.

DESCRIPTION	BATCH 1	BATCH 2	BATCH 3	TOTAL	AVERAGE
STARTUP PROPANE (LBS)	1.5	3.75	2.25	7.5	2.5
STARTUP BIOMASS (LBS)	205	185	150	540	180
RUN FUEL USAGE (LBS)	1025	975	1435	3435	1145
RUN TIME (HRS)	6.0	5.0	6.5	17.5	5.8
START CORN TEMPERATURE (^{o}F)	50	43	43		45.3
END CORN TEMPERATURE (^{o}F)	60	60	60		60
COOLING TIME (HRS)	4	2	2.4	8.4	2.8
CORN DRY MATTER (LBS)	32,033	26,749	31,556	90,338	30,113
CORN INITIAL MOISTURE (%wb)	14.22%	14.36%	17.98%		15.52%
CORN FINAL MOISTURE (%wb)	11.56%	13.18%	13.01%		12.58%
WATER REMOVED (LBS)	1123	425	2198	3746	1249
CORN VOLUME (BUSHELS)	677	565	667	1909	636
RELATIVE HUMIDITY (%)	30%	15%	45%		30%
FUEL FEED RATE (LBS/MIN)	2.85	3.25	3.68		3.26
FUEL MOISTURE CONTENT (%)	13.4%	33.3%	29.4%		25.4%
AIRFLOW RATE (CFM)	11,902	11,273	12,104		11,760
OUTPUT OF BURNER (BTU/HR)	829,000	756,000	795,000		793,333
BURNER EFFICIENCY (%)	76.2%	79.3%	72.6%		76.0%
OVERALL EFFICIENCY (%)	68.6%	70.7%	65.9%		68.4%

The average burner efficiency was 76% and the average overall efficiency was 68.4% based on this data. The losses of heat were due to heat transfer to the air, inefficient fuel combustion, unburned fuel, and loss of fuel between the scales and feeder mechanism. These were losses that would result during normal operation.

Economic Considerations

Capital Costs Of Heat Unit, Feeder System , And Collection System

The marginal capital costs of setting up the prototype biomass-fired heat unit for the grain drying system are outlined in Table 4. Costs were calculated on 1983 invoice prices for materials and freight. Installation labor costs and overhead were estimated as 30% of the invoice prices.

Table 4. Capital costs for biomass burner system.

DESCRIPTION	MATERIAL	FREIGHT	INSTALL	OVERHEAD	TOTAL
BIOMASS BURNER	3818.14	640.00	430.30	1466.53	6354.97
BIOMASS FEED SYSTEM	3064.69	411.19	469.00	1183.46	5128.34
BIOMASS COLLECTION SYSTEM	1322.58		199.75	456.70	1979.03
TOTALS	8205.41	1051.19	1099.05	3106.69	13462.34

The marginal capital costs of setting up a biomass burner and feed system for this batch-in-bin drying system was $11.48/ac/year based on a ten year economic life and 100 acres of corn produced per year. If a 40% investment tax credit for alternative energy projects is utilized the capital costs/ac would be $6.89.

Biomass Fuel Costs

The value of the biomass was figured at \$27.50 per ton. This was determined from the net avoided cost of \$35 per ton for barley straw less \$7.50 per ton due to the higher moisture content of the corn stover. This was a true net avoided cost because it was necessary to buy additional barley straw for bedding in the feedlot at \$35/ton delivered. At this net avoided cost the value of the biomass was \$33.00/ac.

Total biomass fuel used for the three furnace runs was 3975 lbs to dry an equivalent of 13.6 ac of corn. At \$27.50/ton, this totals \$54.66, or \$4.02/ac. It required a total of 7.5 lbs of propane to start the biomass system at a cost of \$1.15, or \$.08/ac. The total cost of fuel to heat the drying air was \$4.10/ac. Propane would cost \$9.56/ac to do the same job assuming 1.37×10^6 BTU/ac, and propane at 93,000 BTU/gallon and \$.65/gallon. It was assumed that fuel costs to move the biomass from storage to the feeder unit was minimal compared to other fuel costs.

Electricity Costs

Electrical costs during the summer of 1984 were \$.024/kwh. The cost for electricity for the three batches was 611 kwh times \$.024 or a total of \$14.66. This is an electricity cost of \$1.08/ac over 13.6 ac.

Labor Costs

Labor costs for collection of biomass and the operation of the biomass drying system were estimated at \$17.80/ac. The costs included a full time operator for the drying system during the drying season

($11.50/ac), an extra person to drive the tractor for unloading the biomass collection wagon ($5.00/ac), and 13% additional time for a combine operator ($1.30/ac). It was assumed that any handling of the biomass at the dryer site was performed by the full time dryer operator.

Labor costs for operating the dryer system with a propane-fired heat unit would be approximately half of the biomass-fired unit. Using a propane-fired heat unit would eliminate the time required for an operator during the drying cycle. The estimated labor costs for the propane drying system was $5.75/ac.

Cost Analysis of Biomass Burner Unit

Table 5 outlines the operating costs of biomass vs propane.

Table 5. Operation costs of biomass vs propane ($/ac).

	CAPITAL	LABOR	ELECTRICITY	FUEL	TOTAL
BIOMASS	$6.89	$11.50	$1.08	$4.10	$23.57
PROPANE	1.00	5.75	1.08	9.56	17.39

Considering labor, fuel, and capital costs, it would not be feasible to install a biomass-fired heat unit instead of a propane-fired heat unit. Factors that could change the feasibility picture would be:

1. More dependable automation of the biomass feeder system.
2. Increased propane costs.
3. Decreased labor and capital costs.
4. Extended system life.
5. Higher acreage and fuel use rate.

Cost Analysis of Biomass Collection

The cost of collecting the biomass was \$1.98/ac in capital costs harvesting 100 ac of corn for 10 years and \$6.30/ac for extra labor. With costs of \$8.28/ac to collect the biomass and \$33.00/ac in net avoided cost using the cobs and stover for feedlot bedding, net returns of \$24.72/ac were possible.

CHAPTER 5

PERFORMANCE MODELLING OF THE BIOMASS-BURNER SYSTEM

The performance of the biomass fired heat unit was simulated with the aid of a computer modelling program in order to predict system performance as changes occurred in ambient air temperature and relative humidity, drying air temperature, fuel moisture content, airflow, and fuel heat content. Development of the model, evaluation of output, and sensitivity analysis of input variables are included below.

Simulation And SLAM

A simulation is a computer model of a system. A system's behavior is predicted, then equations are developed to simulate the behavior. A model of the system is then assembled utilizing the developed equations.

SLAM (Pritsker and Pegden, 1979) is a program for computer modelling of systems in a continuous mode. SLAM is accessed through a MAIN program. Once SLAM is accessed, it initializes variables through a data file of Slam Control Statements, then subroutine STATE is called.

The MAIN program is written by the user, and used for the initialization and calculation of variables that remain constant throughout the simulation run. Subroutine STATE is a FORTRAN program, written by the user, that simulates the performace of the system being modelled. It consists of a set of level, rate, and auxiliary equations, complemented with appropriate FORTRAN programming statements.

System Boundaries And Dynamic Representation

The first stage of evaluating the model was to define the system boundaries. To simplify the model it was necessary to make assumptions about the biomass feed process that would approximate the end results although it may not be a replica of the actual system. One assumption made was that the feed rate would be evaluated at the burn rate. The burn rate is a function of the burner temperature, the amount of fuel in the burner, and airflow rate through the burner. The feed rate is the rate that the biomass is fed into the burner. Once the system is in equilibrium, airflow rates in the system are constant. The temperature in the burner fluctuates within 5 ^{o}F of the thermostat setting. The net effects of the fuel feed rate into the burner was a steady rate of adding heat and moisture to the air stream. The constant feed rate would result in a valid representation of the system.

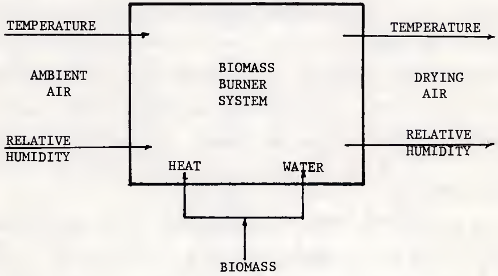

Figure 8. System boundaries, inputs and outputs.

Figure 8 illustrates system boundaries, inputs and outputs. The input variables of temperature and relative humidity are measurable conditions of the air and therefore will be used to represent the condition of the air. The rate at which heat and water are added to the air stream can be calculated from the fuel feed rate and fuel moisture content. The output conditions are then evaluated from these inputs, based on system equations.

Model Development

The system boundaries, actual system behavior, parameter value approximations, and state of the air equations were evaluated to produce the biomass burner model represented in dynamic notation in Figure 9.

The system consists of two loops. The top (positive) loop, represents the effects of the water added to the airstream due to the burning process. An increase in the fuel feed rate increases the amount of water in the air stream. The temperature of the air is lowered and has the effect of increasing the feed rate. The bottom loop is a representation of the effects of the heat added to the air stream. An increase in the fuel feed rate results in an increase of the amount of heat added to the system. This increases the burner temperature and decreases the rate in which the fuel feed rate changes, illustrating a negative loop.

Initial Parameters

Equations and glossary of terms for the ambient air conditions and constants used in the computer simulations are shown below, (MacPhee, 1977, Brooker, 1974, and Brooker, 1966). Definitions and units used are listed following the equations. These equations were used in the MAIN

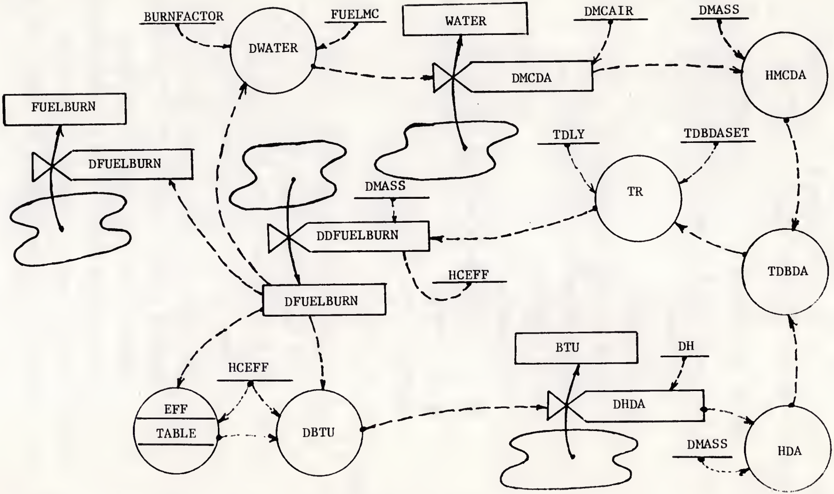

Figure 9. Biomass burner dynamic system diagram.

program. Each of the following parameters were calculated only once since they were constants throughout each run. The equations are written in FORTRAN 77 notation.

```
TABS   = TDB+459.69                                        (5.1)
PS     = EXP(54.6329-12301.688/TABS-5.16923*ALOG(TABS))    (5.2)
PV     = RH*PS                                             (5.3)
RWV    = 85.778                                            (5.4)
HMCAIR = 0.62198*(PV/14.696-PV)                            (5.5)
SPVOLA = HMCAIR*RWV*TABS/144/PV                            (5.6)
DMASS  = DAIR/SPVOLA                                       (5.7)
DMCAIR = HMCAIR*DMASS                                      (5.8)
H      = 0.2405*TDB+HMCAIR*(1061+0.444*TDB)                (5.9)
DH     = H*DMASS                                           (5.10)
HCEFF  = (1-FUELMC)*FUELHC                                 (5.11)
```

where:

DAIR = flow rate of the drying air, cfm

DH = heat flow rate in the air, BTU/min

DMASS = the mass flow rate of the air, lb dry air/min

DMCAIR = moisture flow rate of the system, lb water/min

FUELHC = heat content of the fuel, BTU/lb dry fuel

FUELMC = moisture content of the fuel, lb water/lb wet fuel

H = enthalpy of the ambient air, BTU/lb dry air

HCEFF = effective heat content of the biomass, BTU/lb wet fuel

HMCAIR = moisture content of the ambient air, lb water/lb dry air

PS = saturation vapor pressure of the ambient air, lbs/in^2

PV	=	vapor pressure of ambient air, lbs/in^2
RH	=	relative humidity of the ambient air, decimal
RWV	=	gas constant for water vapor, ft-lb force/lb mass ^oR
SPVOLA	=	specific volume of ambient air, ft^3/lb dry air
TABS	=	absolute temperature of the ambient air, ^oR
TDB	=	dry bulb temperature of the ambient air, ^oF

Moisture Input

Equation 5.13 is used to determine the amount of water that is added to the air stream. As the biomass burns, it evaporates an amount of water equal to the fuel moisture content (FUELMC) times the fuel burn rate (DFUELBURN). Water is also added to the airstream due to the combustion process. This input was estimated by assuming the fuel ultimate analysis to be approximately equal to that of corn cobs. This was done because the analysis for corn cobs was readily available. A mass balance of the combustion process was performed as follows:

$$C_6H_{9.14}O_{4.18} + 6.225\ O_2 = 6\ CO_2 + 4.57\ H_2O \qquad (5.12)$$

The molecular weight of the water in the exhaust due to combustion was compared to the molecular weight of the dry biomass fuel, and an appropriate water-to-fuel ratio was calculated assuming perfect combustion.

DRY BIOMASS FUEL		WATER	
C(12)*6	= 72.00		
H(1)*9.14	= 9.14	H(1)*2*4.57	= 9.14
O(16)*4.18	= 6.88	O(16)*4.57	= 73.12
TOTAL	= 148.02	TOTAL	= 82.36

Water to fuel ratio = 82.36/148.02 = 0.56:1.

The water added from combustion is a function of how much dry fuel is burned. The resulting equation for the amount of water added to the air stream (DWATER) is:

DWATER = FUELMC*DFUELBURN+(1-FUELMC)*DFUELBURN*0.56 (5.13)

where:

DFUELBURN = the rate which the fuel burns, lbs wet fuel/min

DWATER = the moisture added to the drying air due to the moisture content of the fuel and combustion products, lbs water vapor/lb dry air

Heat Input

The amount of heat added to the system (DBTU) was calculated by:

DBTU = HCEFF*DFUELBURN*EFF (5.14)

Fuel Feed Rate

Equations 5.15-5.18 were developed for use in subroutine STATE in the biomass burner system simulation model to represent the fuel feed rate. FUELBURN is the variable used to represent the accumulated fuel use over the course of the run. It is represented in Figure 10, is always increasing, and becomes linear when the system is in equilibrium. The equation for this level is:

FUELBURN = FUELBURN+DFUELBURN*DTNOW (5.15)

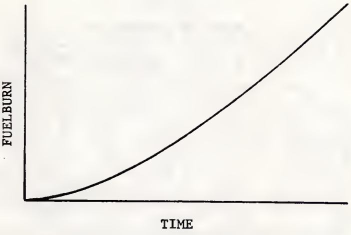

Figure 10. System total fuel use function (FUELBURN).

DFUELBURN is the rate at which the state FUELBURN changes. It is considered to be a level equation in this model with the level DFUELBURN being equal to the rate which the fuel burns. DFUELBURN is a goal seeking rate, reaching a maximum depending upon the set drying temperature (TDBDASET). This behavior is illustrated in Figure 11. The equation that represents the curve is:

$$DFUELBURN = DFUELBURN+DDFUELBURN*DTNOW \tag{5.16}$$

where:

DDFUELBURN = the rate in which the fuel burn rate changes, or the second derivative of the FUELBURN equation.

The corresponding rate equation is:

$$DDFUELBURN = TR*DMASS*0.2405/HCEFF \tag{5.17}$$

where:

TR = the portion of the difference of the actual drying temperature and the desired drying temperature accommodated for during DTNOW.

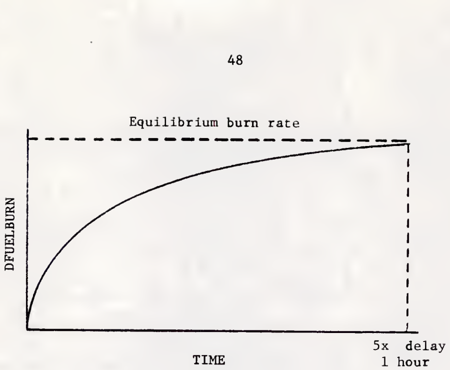

Figure 11. Fuel feed rate function (DFUELBURN).

$$TR = (TDBDASET-TDBDA)/TDLY \tag{5.18}$$

The driving force of the system is the burner trying to burn enough biomass to raise the drying temperature (TDBDA) to the desired drying temperature (TDBDASET). This is accomplished as outlined above by changing the exit air temperature setting of the furnace after accommodating for some delay time (TDLY) for the operator to read the thermometer in the drying plenum and make the adjustment. The delay time also incorporates factors such as the time required to heat up the insulating fire bricks in the burner unit and the time required to accumulate a bed of coals in the bottom of the burner.

The system start-up delay was chosen for convenience. It was not believed that this is the true behavior of the system, yet it is as valid as any other available means of simulating the start-up procedure. It serves the purpose of delaying equilibrium conditions by approximately one hour, matching the usual start-up time for the system.

The results would be the drying air temperature (TDBDA) increasing according to a delayed version of a first order exponential curve with a delay time of 12 minutes as illustrated in Figure 12.

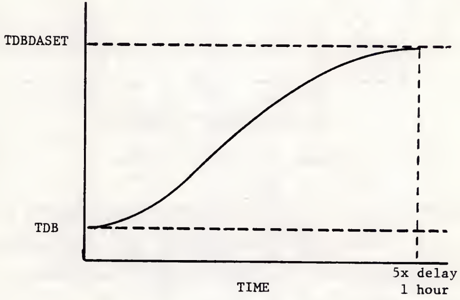

Figure 12. System behavior with delay function.

Burner Efficiency

At 100% burner efficiency the amount of heat added would be equal to the effective heat content of the fuel (HCEFF) times the fuel feed rate. The basic laws of heat transfer require that there be a net loss of energy due to the temperature difference between the system and the environment. Fuel combustion efficiency is dependent upon fuel conditions, burner temperature, and airflow rate through the burner. The combined effects of these relationships is a correlation between overall burner efficiency and net heat output of the system. A system efficiency curve was developed from other direct-fired furnace data (Barrett and Jacko, 1981) and is illustrated in Figure 13.

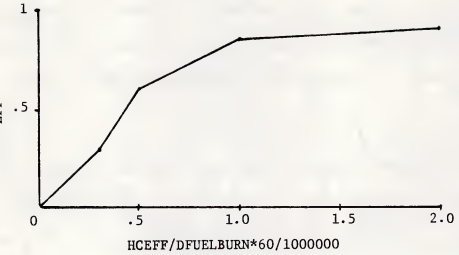

Figure 13. Burner efficiency.

The efficiency was determined in the model using a table function. A table function is a program that interpolates a dependant variable from an independent input assuming a straight line between data input points. The equations used were:

$$EFF = TABLI(EFFVAL, BTUVAL, DBTUTEM, NEFFVAL) \tag{5.19}$$

$$DBTUTEM = HCEFF*DFUELBURN*60/1,000,000 \tag{5.20}$$

where:

BTUVAL = an array of values corresponding to the burner output, BTU/hr

EFFVAL = an array of efficiencies corresponding to system output

NEFFVAL = the number of values in the table lookup

TABLI = function from DYNFUNC for a table lookup at uneven intervals

Output Variables

The state of the drying air at any point in time was determined by:

```
DMCDA = DMCAIR+DWATER                                       (5.21)

DHDA  = DH+DBTU                                             (5.22)
```

where:

DHDA = the heat flow rate in the drying air, BTU/min

DMCDA = the moisture flow rate in the drying air, lb water/min

The following auxiliary equations determined the conditions of the drying air at any point in time.

```
HDA    = DHDA/DMASS                                         (5.23)

HMCDA  = DMCDA/DMASS                                        (5.24)

TDBDA  = (HDA-1061*HMCDA)/(0.2405+0.444*HMCDA)              (5.25)

TABSDA = TDBDA+459.69                                       (5.26)

PVDA   = HMCDA*14.696/(0.62198+HMCDA)                       (5.27)

PSDA = EXP(54.6329-12301.688/TABSDA-5.16923*ALOG(TABSDA)) (5.28)

RHDA   = PVDA/PSDA                                          (5.29)

HMCSAT = 0.62198*(PSDA/(14.696-PSDA))                       (5.30)
```

where:

DHDA = the rate that heat is flowing in the drying air, BTU/min

DMASS = mass rate of flow of dry air, lb air/min

DMCDA = the rate that moisture is flowing in the drying air, lb water vapor/min

HDA = enthalpy of the drying air, BTU/lb dry air

HMCDA = humidity ratio of the drying air, lb water/lb dry air

HMCSAT = the maximum humidity ratio for the drying air, lb water vapor/lb dry air

PSDA = saturation vapor pressure of the drying air, psi

PVDA = vapor pressure of the drying air, psi

RHDA = relative humidity of the drying air, decimal

TABSDA = absolute temperature of the drying air, ^{o}R

TDBDA = dry bulb temperature of the drying air, ^{o}F

Drying Potential

It was necessary to define a performance variable in order to evaluate the model output. The performance variable used was drying potential (DRYPOT), defined as the maximum amount of moisture that the drying air could carry at saturation. This was evaluated by taking the air humidity ratio at the saturation point of the drying air (HMCSAT) and subtracting the humidity ratio of the drying air (HMCDA). In equation form:

$$DRYPOT = (HMCSAT-HMCDA)*DMASS \quad (5.31)$$

DRYPOT is the maximum amount of water that could be removed from the corn in pounds of water per minute, assuming saturation of the exit air from the dryer and no other internal heat losses. The drying potential as defined above was used as a relative comparison between runs.

Model Evaluation

Input Parameter

Initial runs were performed within the limitations outlined in Table 6.

TABLE 6. System limits.

INPUT VARIABLE	LIMITED BY	RANGE
TDB (TEMPERATURE)	DAYS	33-85 F
RH (RELATIVE HUMIDITY)	DAYS	0-100 %
DAIR (AIRFLOW)	CORN DEPTH	13000-18000 CFM
FUELMC (MOISTURE)	MATERIAL	9-45 %
FUELHC (HEAT CONTENT)	MATERIAL	6000-8000 BTU/LB
TDBDASET (DRYING TEMP.)	CORN QUALITY	90-160 F

As outlined in Table 6, the ambient air temperature and relative humidity will vary from day to day. It is usually constant within 10% of a particular value during an individual batch run. The amount of water in the air should remain constant. The relative humidity will decrease as temperature increases if the amount of water in the air does remain constant.

The airflow rate is a direct function of the corn depth and can be varied by altering the corn depth. The fuel heat content and moisture content are characteristics of the particular biomass fuel that is being used in a batch. A corn cob and stover mix has a typical heat content of approximately 7000 - 8000 BTU/lb dry feedstock and a moisture content of about 33%. It is difficult to change fuel parameter values since availability of feedstock is usually limited to one or two sources. The drying air temperature is the easiest variable to change, limited only by drying efficiency and final quality of the dried corn.

Model Output

Appendix VIII summarizes the results of computer simulations. A sensitivity analysis of the model to variation of the input values was performed. Base conditions were established within initial design

values. The base values were increased by a fixed percentage while keeping the other variables fixed at design values in successive runs.

The second column in Table 7 lists the base conditions for this analysis. The third column shows the value used after the 20% incremental increase of each parameter from the base condition. The fourth column represents the percent change in the drying potential that a 20% change in each input variable caused, while column 5 is the corresponding change in fuel use in each run. Fuel use was defined as the steady state fuel burn rate, so the amount of fuel used in a batch run is directly related to fuel use variance.

Table 7. Results of sensitivity analysis.

VARIABLE	BASE	INCREMENTAL INCREASE BY 20% OF BASE	DRYING POT. CHANGE %	FUEL USE CHANGE %
TDB	60 F	72 F	-3.31	16.36
RH	30 %	36 %	-0.44	-----
DAIR	15000 CFM	18000 CFM	20.45	18.18
FUELMC	33 %	39.6 %	-1.04	14.55
FUELHC	7200 BTU/LB	8640 BTU/LB	1.13	-18.18
TDBDASET	130 F	156 F	134.99	36.36

It is interesting to note that the system is most sensitive to the variables that are most easily controlled. The high system sensitivity to the set drying temperature (TDBDASET) was not recognized before this simulation was performed.

Model Comparison To Actual System Performance

The model has been developed thus far to determine the actual system sensitivity to the factors that regulate the state of the drying air. Pertinent conclusions were drawn from the relative results of the

model. Some changes should be made in the model to get output similar to actual burner performance data.

The humidity ratio of the air was calculated (Equations 5.5 and 5.27) assuming an atmospheric pressure of 14.696 psi. This value varies from day to day and also at different points within the system. It varies approximately 10% due to elevation at the test site alone. The barometric pressure at Huntley, Montana is approximately 13-13.5 psi. It was assumed that the variance had negligible effect on the sensitivity of the system to input variables. For fine tuning of the model, this value should be measured the day of the actual runs and that value used for simulation.

Data collected during start-up could be utilized by SLAM's statistical package to better simulate the start-up procedure. Model accuracy using this method of model development would improve as more data is added.

An equation could be developed for the fuel burn rate as a function of burner temperature, amount of fuel in the burner, moisture content of the fuel in the burner, and airflow rate through the burner. The cost of making the above changes thus far outweighed the benefits from the changes.

CHAPTER 6

DISCUSSION

Background

Researchers at several universities are working on the design, use, economics and emissions from biomass burners. Feedstocks such as corn cobs, cord wood, wood chips, and walnut shells have been studied extensively.

Additional research needs to be done on the burning of cereal straw as an alternative heat source. Cereal straw has characteristics dissimilar from many of the feedstocks being studied. Factors such as burn efficiency as compared to fuel moisture content and straw variety would be useful information for future straw burner design.

System Design

Airflow rates were purposely chosen comparatively high for the batch-in-bin drying system studied. This was done in an effort to reduce drying time and utilize the burner at maximum efficiency while keeping the capital costs at a minimum.

Construction

Construction costs play an important role in the feasibility of any project. If a person plans to build a system by himself, careful planning should be done beforehand to minimize the number of problems and delays during construction. Whether a person does his own

construction or has a contractor do the work, someone has to be on top of the scheduling to avoid a delay in completion when a deadline needs to be met.

System Performance

Effect Of Ambient Air Temperatures

When operating in warm weather (60 - 70 ^{o}F), exhaust air from the burner was almost clean, but there was normally still a trace of smoke present. As the ambient air cooled to 20 - 30 ^{o}F, it was possible to achieve a clean burn as defined by lack of visible or olfactory evidence of smoke. This may have been due to increased air flow through the burner during operation at cooler temperatures. Less air was pulled through the system from the tempering valves and more air through the burner in order to maintain desired (>120 ^{o}F) output air temperatures, thus supplying more oxygen for the burning process.

At an ambient air temperature of 20 - 30 ^{o}F, it was possible to obtain a temperature in the heated output air in the drying plenum of only 90 - 100 ^{o}F. This was accomplished by completely closing the downstream air tempering valve and placing the air tempering valve upstream of the burner on the third notch from closed. Low exhaust gas temperatures were in part due to the relatively wet feedstock (corn cobs and stover at 33% mc) used as fuel for this run. It may have been possible to increase drying temperature by further closing the upstream tempering valve. (Data from this test run has not been included in the summary operating statistics of Appendix VIII).

Cold Weather Moisture Removal From Corn

Running the system for four hours with the 95 ^{o}F drying air failed to remove any moisture from a batch of 19% mc corn. The corn was initially at 30 ^{o}F. Factors contributing to the lack of drying included the following:

1. Heat available from the drying air went initially into warming the corn, rather than driving moisture from the kernels.
2. Moisture was present in the warmed air from several sources including the combustion process, high-humidity ambient air (low total moisture from this source), and the high-moisture stover fuel.
3. Moisture present in the drying air condensed out in the relatively cool grain until such time that the grain temperature reached the wet-bulb temperature of the drying air.
4. The relatively low amount of available heat to warm the corn and evaporate the moisture from the corn.

Biomass Equivalence To Hydrocarbon Fuel

Figuring 2400 lbs biomass/ac with a net heat content of 4919 BTU/lb biomass at 33% mc gives a total of 11,805,600 BTU/ac. This is equivalent to 127 gallons of propane at 93,000 BTU/gallon or $82.51/ac if propane is worth $.65 per gallon and 100% of the biomass could be used to replace propane as a heat source at an equivalent efficiency.

Using Barley Straw For Fuel

To eliminate a major problem associated with the moisture in the feedstock, barley straw, a relatively low-moisture fuel, was used in a cold weather furnace run. The two available sources of straw were on-station straw with a 12.5% mc, and off-station straw with a 9.5% mc. These fuels reduced the problems associated with moisture, but created additional problems. It was not possible to get the 9.5% mc straw to burn clean, resulting in deposition of significant amounts of ash and smoke particles in the bin plenum and in the batch of grain. Possible reasons for the incomplete combustion include:

1. Retention time in the burner may not have been adequate with fuels of lower moisture contents. Some of the burning material was discharged from the burner exhaust before combustion was completed.
2. The furnace has a ceramic-based filter in the exhaust manifold that is designed to prevent large unburned particles of fuel from escaping the burner. It also restricts the air flow through the burner, increasing the retention time. Under conditions noted in (1) above, a significant amount of ash collected on the underside of this fixture, and may have had an adverse effect on system performance. The filter effect was probably of less importance than the fuel moisture content.
3. Specific combinations of fuel feed rate and air flow rate through the burner are necessary to ensure complete combustion. The magnitude of each of these flow rates affected burner exhaust gas temperature and was dependent on

other environmental factors including moisture content of the fuel, fuel type, and external air temperature. Additional work needs to be done to determine recommended values for fuel and air flow rates as a function of the environmental factors noted.

Fuel Moisture Content

It appears that burner performance is directly related to fuel moisture content. Desirable air flow rate through the burner also depends on fuel moisture content. For example, corn cobs and stover at 33% mc burn well at 800 - 1000 ^{o}F with an adequate air supply. Attempting to operate the furnace at a higher exhaust temperature with the same air flow rate results in piling of unburnt biomass in the burner and subsequent choking of the fire.

The 12.5% mc straw would not burn without noticeable smoke at ambient air temperatures above 30 ^{o}F, yet it would burn clean at ambient air temperatures between -10 ^{o}F and 10 ^{o}F. Under the latter conditions, the straw would occasionally pile in the burner, indicating that the system was operating at close to its optimum outlet temperature for the given air flow rate. The outlet temperature of the burner would range from 1300 ^{o}F to 1550 ^{o}F while burning low moisture content straw. Operation at a temperature above 1600 ^{o}F was not attempted because of other system construction limitations.

Some observations can be made related to the moisture content calculations for the biomass fuel samples. When comparing spring drying with runs made the previous fall, the corn cobs had equalized in moisture with the stover which resulted in a better burn. Corn cobs did

not accumulate on the bottom of the burner during a burn, even though the average moisture content was 33%, approximately the same as it was the previous fall.

Limiting Factors

Observation of burner performance during the fall of 1983 and the spring of 1984 was the basis for the following hypothesis. The capability of obtaining complete combustion of the fuel varies directly according to:

1. Fuel retention time within the burner.
2. The availability of oxygen in the combustion zone.
3. The rate which heat is removed from the combustion zone.

Considering only the combustion process, extra water in the combustion zone would be more advantageous than not enough water, assuming the rate of heat removal from the combustion zone was the limiting factor. Adding water to the combustion zone would increase the rate of latent heat removal, allowing more heat to be transferred from the combustion zone resulting in a more complete combustion process. The results of adding the water would be more efficient combustion of the fuel.

Lowering the burner inlet air temperature would increase the amount of heat that could be added to the air for an equivalent drying air temperature. The rate of heat removal from the combustion zone would increase, improving efficiency of the the combustion process. This would explain the observed phenomena of more efficient combustion in cold weather using the same feedstock conditions as in warm weather tests.

A higher burner exit air temperature would also increase the rate of heat removal from the combustion zone. An advantage to increased combustion temperature is reduced required retention time in the burner.

Increasing the airflow through the burner increases the rate of heat removal from the burner while decreasing the actual retention time. The increased air flow would result in lower burner temperatures for the same heat output rate, increasing required retention time for complete combustion. Efficiency of fuel combustion could be improved as oulined above by determining the limiting factor(s) of retention time, oxygen level, or rate of heat removal and altering the burner design to decrease the limitations caused by the factor(s).

Mechanical Aspects Of Furnace And Feeder Operation

In general, the furnace operation can be considered good. Some mechanical modifications may help to improve the system reliability and reduce the need for constant monitoring.

Sukup Manufacturing Company has developed a gear motor PTO drive unit to enable use of a forage wagon for a feeder. That type of system worked well with a corn cob and stover blend but did not work at all for straw. It did feed chopped straw well and so did the 9-inch auger. The chopped straw did not burn well because of the presence of snow and the tendency of the chopped straw to compact as it was fed into the burner. Chopped staw could possibly work in this system if the material moisture conditions are improved. Chopping the straw has the advantage of equalizing the moisture throughout the feedstock, reducing the necessity of adjusting the furnace to accommodate changes in fuel moisture content.

Mechanical problems included a primary drive gearbox failure during extremely cold weather operation. It is possible that the feedstocks were frozen in place, requiring excessive power and causing total destruction of the gearbox.

A more persistent and potentially serious problem is the tendency of the horizontal feed auger to plug occasionally. Some plugging has been attributed to the presence of foreign material in the fuel, but other similar events seem to be due to slugging or binding of the feedstock. Corn cobs and stover generally fed through in an acceptable manner, but unchopped straw as delivered from a combine caused some feeding problems. Straw tended to bind on the screw conveyor when surface moisture was present, wrapping around the auger and impeding material flow. This kind of problem required manual clearing, and the presence of an operator to shut-down the system at first signs of failure. If the straw was very dry, it would bridge over the auger and not feed into the burner. Straw, blended with corn cobs and stover, fed satisfactorily. It appeared as though the dense corn cobs acted as a bridge breaker in the feeding mechanism and helped to prevent the straw from wrapping around the auger. Some straw would still wrap around the auger even if it was blended with corn cobs and stover. It would not be possible to fully automate the drying system if current feeding problems could not be eliminated.

Efficiency

Overall system efficiency may be increased by insulating the burner unit and duct work. This is probably not economically feasible due to the short amount of time the burner unit would be in use each year, and

the low value of the fuel. Economically speaking, increasing the overall efficiency of the dryer is not as important as reducing system labor requirements.

Performance Modelling

According the the results of the sensitivity analysis, drying potential of the drying air can be increased by 135% by increasing the temperature of the drying air by 20%. The corresponding fuel usage is increased by only 36%. These results were obtained because the saturation vapor pressure of air is an exponential function of the dry bulb temperature. Actual airflow rate is a critical factor in determining the length of time necessary to dry a batch of corn. Results of simulation runs determined that a 20% increase in airflow results in a 20% increase in drying potential. One of the factors that influences the efficiency of the grain dryer is the velocity of the air past the kernels of corn. Increased air velocity usually results in a lower drying efficiency. Modelling can help determine the most economical airflow rates.

The biomass burner model has much room for expansion. A corn dryer model has been partially developed by David Powell, a graduate student at Montana State University, which could be coupled with this model. Time spent on improving this model could result in decreased capital costs of development in the field. Economic factors could be incorporated into the model, giving printouts of costs changes due to changes in system parameters. Model accuracy could be improved by using data from actual runs to establish efficiency curves and better simulate

start-up procedures. A statistical package in SLAM allows direct entry of data into the system simulation.

Recommendations For Future Work

1. Build and test a heat exchanger that is compatible with this unit.
2. Improve the by-pass unit to prevent smoke from entering the bin during start-up and shut-down.
3. Improvement of the computer model to help determine where improvements need to be made to increase project feasibility by decreasing costs.
4. A more in-depth study of cereal straws, including tests involving varying moisture contents, grain varieties, straw lengths, and storage practices.
5. Development of an economical corn cob and stover compactor to decrease storage space and handling costs.
6. Improvements on the feeder system, or design of a new feeder system to accommodate cereal straws better.
7. Experimentation of combustion completeness as compared to moisture content, fuel retention time in the combustion zone, and heat transfer rates from the combustion zone.

CHAPTER 7

SUMMARY AND CONCLUSIONS

Summary

A biomass-fired corn drying system was designed, constructed from commercially available components, and tested. The burner selection and system design was based upon information obtained from published literature of universities performing similar research.

Cereal straw is a major source of biomass in most agricultural areas of Montana. A biomass burner designed for use in Montana should be able to accommodate cereal straw as well as other feedstocks. A direct-fired incinerator-type furnace was chosen as the most appropriate design, considering the characteristics of unprocessed cereal straw.

Tests were performed using both a corn cob and stover blend and straw for the burner feedstock. The feeding system worked well using the corn cob and stover blend. Improvements must be made to the feed hopper before unprocessed cereal straw can be fed without constant operator attention.

One-fourth of the corn cobs and stover collected from the fields was required to dry all the shelled field corn from 19% to 14% mc. The average moisture content of the biomass was 33% at harvest time. The heat content of a representative sample of corn cobs and stover was measured to be 7342 BTU/lb dry matter.

Costs of setting up and operating the biomass burner and feeder was \$23.57/ac per year based upon 100 acres of corn produced each year and a 10 year economic life of the system. Costs of setting up and operating a propane system would be \$17.39/ac per year to perform the same job. Cost of setting up and operation of the biomass collection system was \$8.28/ac per year based on the same assumptions as above. Net returns were \$33.00/ac less \$8.28/ac or \$24.72/ac for the biomass collected from the 1983 corn crop.

Conclusions

Three factors appear to regulate the efficiency of combustion in this biomass burner. They are: 1) The retention time of the biomass in the furnace, 2) The availability of oxygen in the combustion zone, and 3) The rate in which heat is transferred from the combustion zone. Water added to the system could increase the combustion efficiency by providing a means of increased heat transfer from the combustion zone, assuming the exit air temperature remains constant and the rate of heat transfer is the limiting factor. Colder furnace inlet air could increase the combustion efficiency based on the same line of reasoning and assumptions.

The biomass moisture content plays an important role in the efficiency of the combustion process in this furnace, due to a maximum allowable furnace temperature of 1600 ^{o}F. Low moisture content fuels result in low combustion efficiencies due to inadequate retention time in the furnace. The limiting factor appears to be the rate in which heat is transferred from the combustion zone. Biomass moisture contents between 15% and 35% are desirable for this burner unit assuming the

moisture is uniform throughout the feedstock. Wet spots in the feedstock are undesirable due to choking of the fire and incomplete combustion of the fuel, causing smokey exhaust and contamination of the corn.

The theoretical drying potential of the drying air is 135% greater at 156 ^{o}F than at 140 ^{o}F while the fuel use was only 36% greater. Labor being a major expense, it would be more feasible to operate the furnace to produce drying air temperatures as high as possible without causing damage to the corn.

Complete automation of the system would eliminate the necessity to have a full-time dryer operator, increasing the feasibility of using biomass to dry perishable grains on the farm. This would not be possible without solving the problems associated with feeding cereal straw.

Based on costs figures collected during the 1983 drying season, it would not be feasible to set up and operate the biomass-fired heat unit tested to dry the corn from 100 acres for 10 years, although it would be feasible to collect the biomass for use in a feedlot as bedding.

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APPENDICES

APPENDIX I: Time use efficiency when harvesting stover in addition to corn. November 1983.

In-field harvest operations were observed for a John Deere 55 combine with a Sukup Biomass Collector attachment. Minutes per operation were recorded for sequential activities as noted below. Each line represents combine travel for one field length (1225 ft) and is equivalent to 0.21 acres harvested, based on 3 rows harvested on a 30-inch row spacing. Total field size was 2.74 acres.

Table 8. Field operation times in minutes.

	Combine Harvest Time	Unload Corn to Truck	Change Stover Wagons	Change Wagons and Unload Corn	
	8.82			2.50	
	8.62	2.07			
	8.78			4.00	
	8.82	2.50			
	8.58			2.67	
	8.75	1.75	10.00		
	9.50			3.25	
	9.52	1.82			
	9.98	2.08	3.47		
	8.95	2.17			
	9.70			3.67	
	9.00	2.05			
	9.85			4.25	
Total min:	118.87	14.43	13.47	20.33	167.1
% of total:	71.14	8.64	8.06	12.17	100.0

Summary statistics indicate extra time requirements for stover harvest, as compared to normal harvest techniques:

Total harvest time, min:	167.10
Extra Time for stover harvest:	19.37
% of Total:	11.59
% of Normal:	13.11
Bushels harvested:	378.02
Bushels per acre:	137.87
Acres per hour:	.98

APPENDIX II: Corn cob and stover collection data.

Table 9. Corn cob and stover collection data for representative days during 1983 corn harvest.

DATE	GROSS WT lb	TARE WT lb	NET WT, lb at 33% mc, wb
10/27	4530	3780	750
10/27	5035	3760	1275
10/28	5060	3720	1340
10/28	4450	2890	1560
11/2	4570	2890	1680
11/2	5350	3760	1590
11/2	4600	3705	895
11/2	3850	2890	960
11/3	4650	3760	890
11/3	4320	2890	1430
11/3	5750	3760	1990
11/3	4420	2890	1530
11/3	5360	3760	1600
11/3	4405	2890	1515
11/3	5215	3760	1455
11/3	3220	2890	380
11/3	4250	3760	490
11/3	4255	2890	1365
11/4	5255	3760	1495
11/4	4250	3330	920
11/4	3425	2375	1050
11/4	4300	3330	970
11/4	3400	2375	1025
11/4	4265	3330	935
11/4	3825	2375	1450
11/4	4500	3330	1170
11/4	4250	2375	1875
11/4	4100	2375	1725
11/10	3850	2950	900
11/14	4455	2920	1535
11/14	4880	3750	1130
11/17	4075	2920	1155

Since total harvest data is unavailable, average biomass yield was calculated by using data from the Nov. 4, 1983 harvest:

(12,615 lb. biomass/38,050 lb. corn) x (125.7 bu corn/ac) x

(57.7 lb corn @ 18% mc/1 bu) = 2,400 lb. biomass harvested per acre.

APPENDIX III: Corn collection data.

Table 10. Corn collection data for 1983 corn harvest.

DATE 1983	FIELD IDENTIFICATION	GROSS WT lb	TARE WT lb	CORN NET WT, lb at 18% mc, wb
10/27	A	11800	8960	2940
10/27	G	21165	11900	9265
10/28	G	11710	8435	3275
11/2	P	14415	8435	5980
11/2	P	10740	8435	2305
11/3	P	15785	8965	6870
11/3	P	16225	8965	7260
11/3	P	16350	8965	7385
11/3	P	14900	8965	5950
11/3	P	16501	8965	7561
11/3	P	16750	8965	6810
11/4	P	18260	8965	6260
11/4	P	15100	8965	6140
11/4	G	16230	8960	7270
11/4	G	15160	8870	6290
11/4	G	data missing -	estimated wt:	6780
11/4	G	14180	8870	5310
11/10	O	22720	9680	13640
11/10	O	17450	9070	8380
11/11	O	10910	8660	2250
11/15	A	19210	8930	10280
11/15	O	22570	9020	13550
11/15	O	11115	8925	2190
11/17	G	15840	8925	6915
11/17	G	20215	9085	11125
11/17	G	22220	9085	13135
11/17	G	18600	8920	9680
11/18	G	17760	8915	8845
11/18	G	22100	9080	13020
11/18	G	20500	9060	11440
11/18	G	17860	8910	8950
11/18	G	17665	9050	8615
11/19	G	18550	9050	9500
			TOTAL	255,166

At 60 lb/bu, total yield was 4252 bu. Averaged over 35 acres, the yield was 7290 lb/ac or 121.5 bu/ac.

APPENDIX IV: Biomass fuel moisture content determination.

Table 11. Data for determination of corn cob and stover moisture content. November 1983.

wet wt. grams	oven dry wt. grams	tare grams	moisture content, w.b.
5979	4260	330	30.4%
4737	3272	330	33.2%
4930	3251	330	36.5%
5972	4099	330	33.2%
Average moisture content, wet basis			33%

Theoretical energy content of the cob/stover mix was determined with the aid of Dr. Nancy Roth, MSU Animal Nutrition Lab. A bomb calorimeter test was run on a representative sample, yielding a net heat value of approximately 4080 cal/g (7340 BTU/lb).

The value appears to be typical of straw and other small grains residues. By contrast, wood products have a value of about 4700 cal/g (8500 BTU/lb) for bone dry material. Usual net yield for wood is in the 7000 - 8000 BTU/lb range.

APPENDIX IV: (continued)

Table 12. Data for determination of corn cob and stover moisture content. March 1984.

	SAMPLE #	MATERIAL	TARE WT	WET WT + TARE	DRY WT + TARE	MCWB %
BATCH 1	1COB	STOVER	37.4	398.3	339.0	16.4
	2COB	COBS	37.4	509.3	451.1	12.3
	3COB	STOVER	37.7	391.9	345.4	13.1
	4COB	STOVER	37.7	372.9	330.0	12.8
	5COB	STOVER	37.5	232.4	208.5	12.3
						13.4
BATCH 2	2COB	STOVER	36.1	561.8	376.4	35.3
	3COB	STOVER	36.3	565.3	372.0	36.5
	4COB	COBS	36.4	558.5	404.3	29.5
	5COB	STOVER	37.3	443.3	315.1	31.6
						33.3
BATCH 3	2COB	STOVER	35.6	622.0	454.4	28.6
	3COB	COBS	35.6	947.9	688.1	28.5
	4COB	STOVER	35.8	542.4	403.4	27.4
	5COB	STOVER	35.7	751.0	518.4	32.5
						29.4

APPENDIX V: Biomass burner performance data.

Table 13. Biomass burner performance data. March 1984. Batch 1 cooling cycle.

FUEL FEED RATE =	2.9 LB/MIN	AIRFLOW RATE =	11903 CFM
MASS FLOW RATE =	727.7 LB/MIN	FUEL MC =	13.4 %
RH AMBIENT AIR =	30 %	FUEL HEAT CONT. =	7342 BTU/LB

MIN	DRY AIR TEM	AMB AIR TEM	EX AIR TEM	MC AMB. AIR	ENT. AMB. AIR	MCAIR DRYING AIR	ENT. DRY AIR	HEAT OUT	HEAT IN	EFF.
3	54	48	60	.00235	14.1	.00235	15.5	3164	0	
18	54	48	62	.00235	14.1	.00235	15.5	18983	0	
18	54	48	66	.00235	14.1	.00235	15.5	18983	0	
18	54	48	70	.00235	14.1	.00235	15.5	18983	0	
18	55	50	72	.00253	14.8	.00253	16.0	15825	0	
18	56	50	74	.00253	14.8	.00253	16.2	18989	0	
18	58	51	78	.00263	15.1	.00263	16.8	22158	0	
18	64	56	83	.00316	16.9	.00316	18.8	25348	0	
18	71	57	88	.00328	17.3	.00328	20.7	44369	0	
18	74	59	87	.00352	18.0	.00352	21.6	47560	0	
18	76	60	85	.00365	18.4	.00365	22.3	50743	0	
18	78	61	82	.00378	18.8	.00378	22.9	53927	0	
18	81	62	82	.00392	19.2	.00392	23.8	60287	0	

HEAT RECOVERED DURING COOLING CYCLE = 396319 BTU

APPENDIX V: (continued)

Table 14. Biomass burner performance data. March 1984. Batch 1 drying cycle.

FUEL FEED RATE = 2.9 LB/MIN
MASS FLOW RATE = 727.7 LB/MIN
RH AMBIENT AIR = 30 %
AIRFLOW RATE = 11903 CFM
FUEL MC = 33.3 %
FUEL HEAT CONT. = 7342 BTU/LB

MIN	DRY AIR TEM	AMB AIR TEM	EX AIR TEM	MC AMB. AIR	ENT. AMB. AIR	MCAIR DRYING AIR	ENT. DRY AIR	HEAT OUT	HEAT IN	EFF.
5	133	63	81	.00406	19.6	.00459	37.1	63852	90604	70.5%
18	141	63	80	.00406	19.6	.00459	39.1	255281	326174	78.3%
18	140	64	79	.00421	20.0	.00473	39.0	248995	326174	76.3%
18	142	65	78	.00436	20.4	.00488	39.6	252243	326174	77.3%
18	135	66	77	.00451	20.8	.00504	38.1	226879	326174	69.6%
18	136	66	76	.00451	20.8	.00504	38.4	230059	326174	70.5%
18	138	66	76	.00451	20.8	.00504	38.8	236418	326174	72.5%
18	142	65	76	.00436	20.4	.00488	39.6	252243	326174	77.3%
18	139	66	75	.00451	20.8	.00504	39.1	239597	326174	73.5%
18	140	64	75	.00421	20.0	.00473	39.0	248995	326174	76.3%
18	143	66	75	.00451	20.8	.00504	40.1	252315	326174	77.4%
18	141	66	75	.00451	20.8	.00504	39.6	245956	326174	75.4%
18	140	64	74	.00421	20.0	.00473	39.0	248995	326174	76.3%
18	141	63	74	.00406	19.6	.00459	39.1	255281	326174	78.3%
18	141	62	72	.00392	19.2	.00445	38.9	258390	326174	79.2%
18	140	62	71	.00392	19.2	.00445	38.7	255213	326174	78.2%
18	140	62	67	.00392	19.2	.00445	38.7	255213	326174	78.2%
18	140	62	62	.00392	19.2	.00445	38.7	255213	326174	78.2%
18	138	58	57	.00340	17.6	.00392	37.6	261310	326174	80.1%
18	134	58	52	.00340	17.6	.00392	36.6	248618	326174	76.2%
8	133	55	51	.00305	16.5	.00357	36.0	113242	144966	78.1%
				TOTALS FOR DRYING CYCLE			(BTU)	4904307	6432881	76.2%
				RECLAIM FROM COOLING			(BTU)	369319		
				STARTUP FUEL HEAT USE			(BTU)		1303425	
				TOTALS FOR BOTH CYCLES			(BTU)	5303627	7736306	68.6%

APPENDIX V: (continued)

Table 15. Biomass burner performance data. March 1984. Batch 2 both cycles.

FUEL FEED RATE = 3.25 LB/MIN   AIRFLOW RATE = 11273 CFM
MASS FLOW RATE = 670 LB/MIN   FUEL MC = 33.4 %
RH AMBIENT AIR = 15 %   FUEL HEAT CONT. = 7342 BTU/LB

MIN	DRY AIR TEM	AMB AIR TEM	EX AIR TEM	MC AMB. AIR	ENT. AMB. AIR	MC DRYING AIR	ENT. DRY AIR	HEAT OUT	HEAT IN	EFF.
COOLING CYCLE										
20	63	50	70	.00126	13.4	.00126	16.5	41989	0	
18	65	52	75	.00136	14.0	.00136	17.1	37797	0	
18	70	55	78	.00152	14.9	.00152	18.5	43624	0	
18	73	57	77	.00163	15.5	.00163	19.3	46542	0	
18	75	60	77	.00182	16.4	.00182	20.0	43648	0	
18	80	62	77	.00195	17.0	.00195	21.4	52391	0	
11	84	64	80	.00210	17.7	.00210	22.5	35584	0	
HEAT RECOVERED FROM COOLING CYCLE = 301557 BTU										
DRYING CYCLE										
18	142	66	78	.00225	18.3	.00387	38.5	243290	286052	85.1%
18	142	67	77	.00233	18.7	.00395	38.6	240409	286052	84.0%
18	142	67	77	.00233	18.7	.00395	38.6	240409	286052	84.0%
18	141	68	77	.00241	19.0	.00403	38.4	234607	286052	82.0%
18	143	70	78	.00258	19.7	.00420	39.1	234692	286052	82.0%
18	145	70	78	.00258	19.7	.00420	39.6	240537	286052	84.1%
18	145	72	78	.00276	20.3	.00438	39.8	234780	286052	82.1%
18	146	73	78	.00286	20.7	.00448	40.2	234826	286052	82.1%
18	146	74	77	.00296	21.0	.00458	40.3	231949	286052	81.1%
18	146	72	77	.00276	20.3	.00438	40.0	237704	286052	83.1%
18	146	70	76	.00258	19.7	.00420	39.8	243460	286052	85.1%
18	146	70	75	.00258	19.7	.00420	39.8	243460	286052	85.1%
18	140	73	74	.00286	20.7	.00448	38.7	217281	286052	76.0%
18	138	72	68	.00276	20.3	.00438	38.1	214315	286052	74.9%
18	134	70	57	.00258	19.7	.00420	36.9	208388	286052	72.8%
18	122	72	47	.00276	20.3	.00438	34.2	167537	286052	58.6%
10	116	70	47	.00258	19.7	.00420	32.6	86545	158918	54.5%
TOTALS FOR DRYING CYCLE (BTU)								3754189	4735744	79.3%
HEAT RECLAIM COOLING (BTU)								301557		
STARTUP FUEL HEAT USE (BTU)									1002403	
TOTALS FOR BOTH CYCLES (BTU)								4055764	5738147	70.7%

APPENDIX V: (continued)

Table 16. Biomass burner performance data. March 1984. Batch 3 cooling cycle.

FUEL FEED RATE =	3.68 LB/MIN	AIRFLOW RATE =	12104 CFM
MASS FLOW RATE =	709 LB/MIN	FUEL MC =	29.4 %
RH AMBIENT AIR =	45 %	FUEL HEAT CONT. =	7342 BTU/LB

MIN	DRY AIR TEM	AMB AIR TEM	EX AIR TEM	MC AMB. AIR	ENT. AMB. AIR	MC DRY AIR	ENT. DRY AIR	HEAT OUT	HEAT IN	EFF.
18	51	44	54	.00303	13.9	.00303	15.6	21609	0	
18	50	42	57	.00281	13.1	.00281	15.1	24686	0	
18	49	40	64	.00260	12.4	.00260	14.6	27761	0	
18	50	41	74	.00270	12.8	.00270	14.9	27766	0	
18	51	41	73	.00270	12.8	.00270	15.2	30851	0	
18	54	43	70	.00292	13.5	.00292	16.2	33950	0	
18	58	44	69	.00303	13.9	.00303	17.2	43218	0	
18	64	46	72	.00327	14.6	.00327	19.0	55590	0	

HEAT RECOVERED DURING COOLING CYCLE = 265431 BTU

APPENDIX V: (continued)

Table 17. Biomass burner performance data. March 1984. Batch 3 drying cycle.

FUEL FEED RATE = 3.68 LB/MIN
MASS FLOW RATE = 709 LB/MIN
RH AMBIENT AIR = 45 %

AIRFLOW RATE = 12104 CFM
FUEL MC = 29.4 %
FUEL HEAT CONT. = 7342 BTU/LB

MIN	DRY AIR TEM	AMB AIR TEM	EX AIR TEM	MC AMB. AIR	ENT. AMB. AIR	MC DRY AIR	ENT. DRY AIR	HEAT OUT	HEAT IN	EFF.
17	103	52	74	.00410	17.0	.00563	31.0	169338	324277	52.2%
18	130	52	74	.00410	17.0	.00563	37.6	263045	343352	76.6%
18	134	53	74	.00426	17.4	.00578	38.7	272429	343352	79.3%
18	136	56	74	.00475	18.6	.00628	39.7	269578	343352	78.5%
18	137	58	74	.00511	19.5	.00664	40.4	266650	343352	77.7%
18	120	58	75	.00511	19.5	.00664	36.3	213824	343352	62.3%
18	131	62	74	.00590	21.3	.00743	39.8	235919	343352	68.7%
18	137	64	73	.00633	22.3	.00786	41.8	248563	343352	72.4%
18	140	64	73	.00633	22.3	.00786	42.5	257906	343352	75.1%
18	140	64	74	.00633	22.3	.00786	42.5	257906	343352	75.1%
18	136	62	76	.00590	21.3	.00743	41.0	251478	343352	73.2%
18	124	65	73	.00656	22.8	.00809	38.8	205047	343352	59.7%
18	134	64	74	.00633	22.3	.00786	41.0	239220	343352	69.7%
18	137	63	73	.00611	21.8	.00764	41.5	251577	343352	73.3%
18	137	65	73	.00656	22.8	.00809	42.0	245550	343352	71.5%
18	137	66	73	.00680	23.3	.00832	42.3	242538	343352	70.6%
18	138	64	72	.00633	22.3	.00786	42.0	251678	343352	73.3%
18	137	63	71	.00611	21.8	.00764	41.5	251577	343352	73.3%
18	139	65	69	.00656	22.8	.00809	42.5	251782	343352	73.3%
18	140	63	56	.00611	21.8	.00764	42.2	260916	343352	76.0%
18	142	65	47	.00656	22.8	.00809	43.2	261129	343352	76.1%
18	132	64	48	.00633	22.3	.00786	40.5	232992	343352	67.9%

TOTALS FOR DRYING CYCLE	(BTU)	5231304	7210389	72.6%
RECLAIM COOLING CYCLE	(BTU)	265431		
STARTUP FUEL HEAT USE	(BTU)		1062608	
TOTAL FUEL USAGE	(BTU)	5666072	8597273	65.9%

APPENDIX VI: Corn moisture content determination.

Table 18. Data for determination of corn moisture content. November, 1983.

SAMPLE	WET+ TARE g	DRY+ TARE g	WATER g	TARE g	ACTUAL M.C. W.B.	CORN LBS REP	WATER LBS REM	BUSHELS 15.5% M.C.	WATER LBS TOT
1	348.22	285.25	62.97	6.52	18.43	12463	431.9	214.83	2296.65
2	349.21	284.25	64.96	6.52	18.96	12463	509.7	213.44	2362.38
3	342.00	279.65	62.35	6.52	18.59	12463	455.0	214.42	2316.19
4	330.37	269.79	60.58	6.52	18.71	12463	472.8	214.10	2331.26
					18.67	49850	1869.5	856.79	9306.48

Data for corn moisture content samples taken 11/11/83 from the transport truck at the bin fill auger.

Table 19. Data for determination of corn moisture content. November 11, 1983.

SAMPLE	WET+ TARE g	DRY+ TARE g	WATER g	TARE g	ACTUAL M.C. W.B.	CORN LBS REP	WATER LBS REM	BUSHELS 15.5% M.C.	WATER LBS TOT
A1	669.25	544.11	125.14	6.52	18.88	6820	273.00	116.91	1287.79
A2	568.08	468.35	99.73	6.52	17.76	6820	182.36	118.53	1211.19
A3	596.49	485.52	110.97	6.52	18.81	4190	164.10	71.89	788.12
A4	595.10	487.07	108.03	6.52	18.35	4190	141.53	72.29	769.05
A5	638.44	525.11	113.33	6.52	17.93	2250	64.82	39.02	403.52
A6	545.32	465.21	80.11	6.52	14.87	5140	-38.43	92.47	764.23
A7	581.12	495.30	85.82	6.52	14.94	5140	-34.33	92.40	767.69
A8	593.26	486.23	107.03	6.52	18.24	6775	219.80	117.06	1235.86
A9	595.76	489.67	106.09	6.52	18.00	6775	200.81	117.40	1219.81
A10	579.46	474.25	105.21	6.52	18.36	2204	74.68	38.02	404.72
					17.60	50304	1248.35	875.99	8851.97

As a check on the in-truck sampling technique, ten additional samples were taken by probing the grain after filling the bin. The net sample was well-blended and then four subsamples were taken for corn moisture content determination. As noted by the average moisture content, results were the same, so the truck sampling technique was adopted for general use.

APPENDIX VI: (continued)

Table 20. Data for determination of corn moisture content. November 11, 1983.

SAM-PLE	WET+ TARE g	DRY+ TARE g	WATER g	TARE g	ACTUAL M.C. W.B.	CORN LBS REP	WATER LBS REM	BUSHELS 15.5% M.C.	WATER LBS TOT
S1	365.75	302.75	63.00	6.52	17.54	12576	303.24	219.16	2205.52
S2	326.86	270.56	56.30	6.52	17.58	12576	308.83	219.06	2210.24
S3	335.12	277.25	57.87	6.52	17.61	12576	314.19	218.96	2214.77
S4	338.23	279.66	58.57	6.52	17.66	12576	321.02	218.84	2220.54
					17.60	50304	1247.28	876.01	8851.07

Table 21. Data for determination of initial corn moisture content. November 14, 1983.

SAM-PLE	WET+ TARE g	DRY+ TARE g	WATER g	TARE g	ACTUAL M.C. W.B.	CORN LBS REP	WATER LBS REM	BUSHELS 15.5% M.C.	WATER LBS TOT
B1	658.62	542.37	116.25	6.52	17.83	3458	95.22	60.04	616.37
B2	596.57	494.07	102.50	6.52	17.37	3458	76.57	60.37	600.62
B3	586.94	481.62	105.32	6.52	18.15	5563	174.15	96.22	1009.34
B4	595.81	489.93	105.88	6.52	17.97	5563	162.42	96.43	999.44
B5	626.81	517.20	109.61	6.52	17.67	6568	168.72	114.26	1160.53
B6	549.45	452.76	96.69	6.52	17.81	6568	179.45	114.07	1169.60
B7	540.99	448.50	92.49	6.52	17.30	4840	103.39	84.58	837.56
B8	645.47	534.26	111.21	6.52	17.41	4840	109.12	84.48	842.41
B9	454.00	373.90	80.10	6.52	17.90	4423	125.62	76.73	791.64
B10	488.96	401.15	87.81	6.52	18.20	4423	141.37	76.45	804.95
B11	631.17	517.69	113.48	6.52	18.17	6510	205.47	112.58	1182.67
B12	480.00	392.53	87.47	6.52	18.47	6510	229.11	112.16	1202.65
B13	609.96	499.20	110.76	6.52	18.35	5720	193.25	98.69	1049.89
B14	470.00	381.57	88.43	6.52	19.08	5720	242.31	97.82	1091.35
B15	829.10	677.59	151.51	6.52	18.42	8615	297.59	148.53	1586.79
B16	480.00	392.53	87.47	6.52	18.47	8950	314.98	154.20	1653.41
B17	480.00	392.53	87.47	6.52	18.47	9500	334.34	163.67	1755.02
					18.13	101225	3153.08	1751.28	18354.22

Samples were taken from the dump hopper at the drying bin.

APPENDIX VI: (continued)

Table 22. Data for determination of initial corn moisture content. Batch 1 of March, 1984.

SAMPLE	TARE WT	WET WT	DRY WT	NET WET	NET DRY	% MC WB	
1W11	50.06	88.93	83.42	38.87	33.36	14.18	
1W12	50.09	90.79	85.10	40.70	35.01	13.98	
1W13	50.15	92.03	86.18	41.88	36.03	13.97	
1W14	50.09	92.32	86.64	42.23	36.55	13.45	
1W15	50.06	109.54	102.06	59.48	52.00	12.58	13.54
1W21	50.06	101.96	94.16	51.90	44.10	15.03	
1W22	49.89	90.93	84.92	41.04	35.03	14.64	
1W23	50.03	93.30	87.16	43.27	37.13	14.19	
1W24	50.14	91.91	85.85	41.77	35.71	14.51	
1W25	50.08	105.85	98.72	55.77	48.64	12.78	14.18
1W31	50.05	99.03	91.26	48.98	41.21	15.86	
1W32	50.14	88.84	83.00	38.70	32.86	15.09	
1W33	50.08	92.87	86.34	42.79	36.26	15.26	
1W34	50.07	88.73	83.32	38.66	33.25	13.99	
1W35	50.03	106.39	98.98	56.36	48.95	13.15	14.62
1W41	50.04	91.04	84.49	41.00	34.45	15.98	
1W42	50.11	91.91	85.59	41.80	35.48	15.12	
1W43	50.15	96.23	89.26	46.08	39.11	15.13	
1W44	50.07	94.04	87.75	43.97	37.68	14.31	
1W45	50.11	117.81	108.98	67.70	58.87	13.04	14.53

INITIAL MOISTURE CONTENT (%) = 14.22

APPENDIX VI: (continued)

Table 23. Data for determination of final corn moisture content. Batch 1 of March, 1984.

SAMPLE	TARE WT	WET WT	DRY WT	NET WET	NET DRY	% MC WB	
1D11	50.15	85.28	80.56	35.13	30.41	13.44	
1D12	50.12	93.14	87.74	43.02	37.62	12.55	
1D13	50.13	87.94	83.59	37.81	33.46	11.50	
1D14	50.04	91.52	87.10	41.48	37.06	10.66	
1D15	50.04	100.60	95.84	50.56	45.80	9.41	11.37
1D21	50.08	91.53	85.48	41.45	35.40	14.60	
1D22	50.14	94.70	88.93	44.56	38.79	12.95	
1D23	50.01	96.81	91.42	46.80	41.41	11.52	
1D24	50.08	94.77	90.11	44.69	40.03	10.43	
1D25	50.16	116.55	110.27	66.39	60.11	9.46	11.54
1D31	49.95	90.01	84.06	40.06	34.11	14.85	
1D32	50.02	87.05	82.29	37.03	32.27	12.85	
1D33	49.93	94.05	88.85	44.12	38.92	11.79	
1D34	50.11	93.90	89.14	43.79	39.03	10.87	
1D35	50.05	112.92	107.04	62.87	56.99	9.35	11.65
1D41	50.06	85.33	80.24	35.27	30.18	14.43	
1D42	50.15	93.63	88.13	43.48	37.98	12.65	
1D43	50.07	95.59	90.26	45.52	40.19	11.71	
1D44	50.14	95.59	90.58	45.45	40.44	11.02	
1D45	50.11	116.39	109.81	66.28	59.70	9.93	11.66
				FINAL MOISTURE CONTENT (%) =			11.56

APPENDIX VI: (continued)

Table 24. Data for determination of initial corn moisture content. Batch 2 of March, 1984.

SAMPLE	TARE WT	WET WT	DRY WT	NET WET	NET DRY	% MC WB	
2W11	50.08	101.40	94.04	51.32	43.96	14.34	
2W12	50.13	93.90	87.59	43.77	37.46	14.42	
2W13	44.92	86.55	80.53	41.63	35.61	14.46	
2W14	50.15	94.13	87.71	43.98	37.56	14.60	
2W15	50.08	72.96	69.66	22.88	19.58	14.42	14.45
2W21	50.08	93.61	87.61	43.53	37.53	13.78	
2W22	44.03	70.48	66.80	26.45	22.77	13.91	
2W23	50.07	87.11	82.10	37.04	32.03	13.53	
2W24	50.11	90.44	84.99	40.33	34.88	13.51	
2W25	44.19	65.82	63.05	21.63	18.86	12.81	13.56
2W31	50.04	86.61	81.77	36.57	31.73	13.23	
2W32	50.03	90.86	85.18	40.83	35.15	13.91	
2W33	45.11	83.04	77.73	37.93	32.62	14.00	
2W34	50.10	88.35	82.80	38.25	32.70	14.51	
2W35	50.08	70.47	67.74	20.39	17.66	13.39	13.86
2W41	50.07	91.38	84.74	41.31	34.67	16.07	
2W42	49.96	93.71	86.77	43.75	36.81	15.86	
2W43	44.52	85.60	79.24	41.08	34.72	15.48	
2W44	50.05	90.52	84.19	40.47	34.14	15.64	
2W45	50.10	72.72	69.43	22.62	19.33	14.54	15.62
				INITIAL MOISTURE CONTENT (%) =			14.37

APPENDIX VI: (continued)

Table 25. Data for determination of final corn moisture content. Batch 2 of March, 1984.

SAMPLE	TARE WT	WET WT	DRY WT	NET WET	NET DRY	% MC WB	
2D11	49.96	97.15	89.72	47.19	39.76	15.74	
2D12	50.10	95.48	88.96	45.38	38.86	14.37	
2D13	50.13	93.85	88.20	43.72	38.07	12.92	
2D14	50.08	94.34	89.33	44.26	39.25	11.32	
2D15	50.17	73.95	71.53	23.78	21.36	10.18	13.23
2D21	50.14	83.20	78.00	33.06	27.86	15.73	
2D22	50.04	96.75	90.12	46.71	40.08	14.19	
2D23	50.16	93.97	88.46	43.81	38.30	12.58	
2D24	50.06	92.93	88.15	42.87	38.09	11.15	
2D25	50.01	74.40	71.95	24.39	21.94	10.05	12.87
2D31	50.08	91.73	85.37	41.65	35.29	15.27	
2D32	50.09	94.66	88.24	44.57	38.15	14.40	
2D33	49.88	93.94	88.25	44.06	38.37	12.91	
2D34	50.05	91.17	86.59	41.12	36.54	11.14	
2D35	50.11	70.89	68.78	20.78	18.67	10.15	13.09
2D41	50.07	86.65	80.75	36.58	30.68	16.13	
2D42	50.07	92.58	86.23	42.51	36.16	14.94	
2D43	50.15	92.50	86.89	42.35	36.74	13.25	
2D44	50.11	90.55	85.79	40.44	35.68	11.77	
2D45	50.13	73.78	71.29	23.65	21.16	10.53	13.53
				FINAL MOISTURE CONTENT (%) =			13.18

APPENDIX VI: (continued)

Table 26. Data for determination of initial corn moisture content. Batch 3 of March, 1984.

SAMPLE	TARE WT	WET WT	DRY WT	NET WET	NET DRY	% MC WB	
3W11	50.09	93.35	85.90	43.26	35.81	17.22	
3W12	50.15	89.66	82.69	39.51	32.54	17.64	
3W13	50.14	91.41	84.02	41.27	33.88	17.91	
3W14	50.16	88.71	81.77	38.55	31.61	18.00	
3W15	49.96	109.22	98.26	59.26	48.30	18.49	17.90
3W21	50.16	96.08	87.95	45.92	37.79	17.70	
3W22	50.09	91.04	83.80	40.95	33.71	17.68	
3W23	50.02	94.00	86.09	43.98	36.07	17.99	
3W24	50.05	92.43	84.71	42.38	34.66	18.22	
3W25	50.09	115.02	102.88	64.93	52.79	18.70	18.11
3W31	50.16	86.55	80.10	36.39	29.94	17.72	
3W32	49.88	88.62	81.90	38.74	32.02	17.35	
3W33	50.06	93.85	86.10	43.79	36.04	17.70	
3W34	50.07	89.45	82.42	39.38	32.35	17.85	
3W35	50.18	116.03	103.83	65.85	53.65	18.53	17.91
3W41	50.08	86.91	80.45	36.83	30.37	17.54	
3W42	50.05	92.26	84.93	42.21	34.88	17.37	
3W43	50.11	96.01	87.81	45.90	37.70	17.86	
3W44	50.13	94.78	86.61	44.65	36.48	18.30	
3W45	50.08	119.53	106.69	69.45	56.61	18.49	17.99
				INITIAL MOISTURE CONTENT (%) =			17.98

APPENDIX VI: (continued)

Table 27. Data for determination of final corn moisture content. Batch 3 of March, 1984.

SAMPLE	TARE WT	WET WT	DRY WT	NET WET	NET DRY	% MC WB	
3D11	50.15	89.76	83.66	39.61	33.51	15.40	
3D12	50.05	93.39	86.89	43.34	36.84	15.00	
3D13	50.14	95.58	89.34	45.44	39.20	13.73	
3D14	50.15	94.44	88.92	44.29	38.77	12.46	
3D15	50.08	118.26	110.99	68.18	60.91	10.66	13.13
3D21	50.07	88.11	82.14	38.04	32.07	15.69	
3D22	50.08	92.70	86.37	42.62	36.29	14.85	
3D23	50.02	94.09	88.22	44.07	38.20	13.32	
3D24	50.07	92.39	87.28	42.32	37.21	12.07	
3D25	50.07	120.05	112.61	69.98	62.54	10.63	12.96
3D31	50.09	85.10	79.67	35.01	29.58	15.51	
3D32	50.18	93.78	87.28	43.60	37.10	14.91	
3D33	50.09	94.91	88.81	44.82	38.72	13.61	
3D34	49.96	94.80	89.40	44.84	39.44	12.04	
3D35	50.16	120.19	112.69	70.03	62.53	10.71	12.98
3D41	50.05	82.58	77.55	32.53	27.50	15.46	
3D42	50.12	90.89	85.03	40.77	34.91	14.37	
3D43	50.11	95.62	89.45	45.51	39.34	13.56	
3D44	50.16	93.52	88.19	43.36	38.03	12.29	
3D45	50.07	115.89	108.75	65.82	58.68	10.85	12.95
				FINAL MOISTURE CONTENT (%) =			13.01

APPENDIX VII: Results of simulation runs.

Table 28. Input conditions for biomass burner simulation runs.

RUN	(TDB) AMBIENT TEMP. F	(RH) AMBIENT RH DEC.	(DAIR) AIRFLOW RATE CFM	(TDBDA) DRYING TEMP F	(FUELMC) FUEL MC DEC.	(FUELHC) FUEL HEAT CONTENT BTU/LB
BASE	60	.3	15000	130	.33	7200
BASE85182	60	.3	15000	130	.33	7200
84754	33	.3	15000	130	.33	7200
84755	85	.3	15000	130	.33	7200
84756	60	.05	15000	130	.33	7200
84758	60	.95	15000	130	.33	7200
84759	60	.3	13000	130	.33	7200
84760	60	.3	18000	130	.33	7200
84762	60	.3	15000	90	.33	7200
84763	60	.3	15000	160	.33	7200
84764	60	.3	15000	130	.1	7200
84765	60	.3	15000	130	.5	7200
84766	60	.3	15000	130	.33	6000
84767	60	.3	15000	130	.33	8000
BASE85182	60	.3	15000	130	.33	7200
85899	60	.3	15000	130	.33	8640
85896	72	.3	15000	130	.33	7200
85897	60	.36	15000	130	.33	7200
85898	60	.3	15000	130	.396	7200
84760	60	.3	18000	130	.33	7200
84763	60	.3	15000	156	.33	7200

APPENDIX VII: (continued)

Table 29. Output of biomass burner simulation runs.

RUN NUMBER	(DRYPOT) DRYING POTENTIAL	(FUELBURN) FUEL USE	% CHANGE DRY POT	% CHANGE FUELUSE	(DFUELBURN) FUEL FEED RATE	$\frac{LB\ H_2O}{LB\ FUEL}$
BASE	118.6	241.9	.00	.00	5	23.72
BASE85182	114.9	260.3	-3.12	7.61	5.5	20.89
84754	120.9	365.5	5.22	40.41	7.8	15.50
84755	107.7	171.5	-6.27	-34.11	3.6	29.92
84756	118.7	260.5	3.31	.08	5.5	21.58
84758	105.3	259.6	-8.36	-.27	5.5	19.15
84759	99.45	229	-13.45	-12.02	4.9	20.30
84760	138.4	306	20.45	17.56	6.5	21.29
84762	29.21	132.2	-74.58	-49.21	2.8	10.43
84763	309.3	360.9	169.19	38.65	7.7	40.17
84764	117.5	184.3	2.26	-29.20	3.9	30.13
84765	110.5	373.9	-3.83	43.64	8.2	13.48
84766	113.3	321.4	-1.39	23.47	7	16.19
84767	115.7	231	.70	-11.26	4.9	23.61
BASE85182	114.9	260.3	.00	.00	5.5	20.89
85899	116.2	211.9	1.13	-18.59	4.5	25.82
85896	111.1	215.6	-3.31	-17.17	4.6	24.15
85897	114.4	260.2	-.44	-.04	5.5	20.80
85898	113.7	295.1	-1.04	13.37	6.3	18.05
84760	138.4	306	20.45	17.56	6.5	21.29
84763	270	347.2	134.99	33.38	7.4	36.49

APPENDIX VIII: Data summary for some successful biomass-fired furnace - corn dryer runs.

Run #2 was a mix of two batches of grain.
Run #3 is a continuation of Run #2. October 1983.

Table 30. Data summary for 4 batches run in November of 1983.

Batch #:	1	2	3	4
Corn:				
Batch size, lb	53117	(15455+25650)	39263	50304
Initial mc, wb	19.1	19.1 22	17.2	17.6
Final mc, wb	12.1	17.2	14.7	15.5
Fuel:				
Type	straw	straw-stover	straw-stover	straw-stover
mc, wb	12.5	~23.	~23.	~23.
approx. amount used, lb:	800	1200	1300	1200
Dryer parameters:				
Est. airflow, CFM	17500.0	17500.0	17500.0	17500.0
Temp, ^{o}F	120.0	115.0	110.0	120.0
Lb. H_2O removed:	4246.7	1841.6	1173.1	1250.2
Lb. H_2O removed/hr	1061.7	837.1	553.3	568.3
Drying time, hr	4.0	2.2	2.1	2.2
Cooling/tempering time, hr	7.0	4.0	2.5	7.0

APPENDIX IX: Summary of the variables used in the simulation program.

AIRFLOW = flow rate of the drying air (cubic feet/min)
DBTU = heat added due to burning of the fuel (BTU/min)
DDFUELBURN = the rate in which the fuel burn rate changes with time (lb fuel/min/min)
DFUELBURN = the rate which the fuel burns (lb/min)
DH = the rate that heat is flowing in the ambient air (BTU/min)
DHDA = the rate that heat is flowing in the drying air (BTU/min)
DMASS = mass rate of flow of the dry air (lb air/min)
DMCAIR = the rate that moisture is flowing in the ambient air (lb water vapor/min)
DMCDA = the rate that moisture is flowing in the drying air (lb water vapor/min)
DRYPOT = the potential amount of water that can be carried by the drying air (lb water vapor/min)
DWATER = moisture added to the drying air due to the moisture content of the fuel and combustion products (lb water vapor/lb dry air)
EFF = a table representing the efficiency of the burner (dec)
FUELBURN = the amount of fuel burned up until time DTNOW (lb fuel)
FUELHC = heat content of the fuel (BTU/lb fuel)
FUELMC = moisture content of the fuel (lb water/lb fuel)
H = enthalpy of the ambient air (BTU/lb dry air)
HCEFF = the effective heat content of biomass fuel (BTU/lb wet fuel)
HDA = enthalpy of the drying air (BTU/lb dry air)
HMCAIR = moisture content of the ambient air (lb water/lb dry air)
HMCDA = humidity ratio of the drying air (lb water/lb dry air)
HMCSAT = the maximum humidity ratio for the drying air (lb water vapor/lb dry air)
PS = saturation vapor pressure of the ambient air (lbs/sq in)
PSDA = saturation vapor pressure of the drying air (lbs/sq in)
PV = vapor pressure of ambient air (pounds/sq in)
PVDA = vapor pressure of the drying air (lbs/sq in)
RH = relative humidity of the ambient air (decimal)
RHDA = relative humidity of the drying air (decimal)
RWV = gas constant for water vapor
SPVOLA = specific volume of ambient air (cubic feet/lb dry air)
TABS = absolute temperature of the ambient air (^{o}R)
TABSDA = absolute temperature of the drying air (^{o}R)
TDB = dry bulb temperature of the ambient air (^{o}F)
TDBDA = dry bulb temperature of the drying air (^{o}F)
TDBDASET = the desired set dry bulb temperature of the drying air (^{o}F)
TDLY = delay in TDBDA reaching its goal of TDBDASET (min)
TR = a delayed version of the difference between the desired drying temperature and the actual drying temperature (^{o}F)

APPENDIX X: Listings of the programs used in conjunction with SLAM for the performance modelling of the biomass burner system.

FORTRAN 77 is the language used to write these programs.

MAIN program. BIO3MAIN:FOR

```
C
      DIMENSION NSET(1000)
      COMMON QSET(1000)
      EQUIVALENCE (NSET(1),QSET(1))
C
      INCLUDE BIO3COM1:FOR
      INCLUDE SCOM1:FOR
      INCLUDE BIO2COM1:FOR
      INCLUDE BIO2TAB1:FOR
C
C: Set up the SLAM I/O units, etc.
C
      NCRDR = 5
      NPRNT = 6
      NTAPE = 7
      NNSET = 1000
C
C: Calculate Ambient Air Conditions:
C
      INPUT(LTRMI) TDB,RH,DAIR,TDBDASET,TDLY,FUELMC,FUELHC
C
C
      TABS = TDB+459.69
      PS = EXP(54.6329-12301.688/TABS-5.16923*ALOG(TABS))
      PV = RH*PS
      RWV = 85.788
      HMCAIR = 0.62198*(PV/(14.696-PV))
      SPVOLA = HMCAIR*RWV*TABS/144/PV
      DMASS = DAIR/SPVOLA
      DMCAIR = HMCAIR*DMASS
      H = 0.2405*TDB+HMCAIR*(1061+0.444*TDB)
      DH = H*DMASS
      HCEFF = (1-FUELMC)*FUELHC
C
C: Write out conditions:
C
      WRITE (LTRMO,*) 'TEMPERATURE=',TDB
      WRITE (LTRMO,*) 'RELATIVE HUMIDITY=',RH
      WRITE (LTRMO,*) 'AIRFLOW RATE=',DAIR
      WRITE (LTRMO,*) 'DESIRED DRYING TEMPERATURE=',TDBDASET
      WRITE (LTRMO,*) 'DELAY TIME=',TDLY
      WRITE (LTRMO,*) 'ABSOLUTE TEMPERATURE=',TABS
      WRITE (LTRMO,*) 'SATURATION VAPOR PRESSURE=',PS
      WRITE (LTRMO,*) 'PARTIAL PRESSURE=',PV
      WRITE (LTRMO,*) 'AIR HUMIDITY RATIO=',HMCAIR
      WRITE (LTRMO,*) 'SPECIFIC VOLUME OF AIR=',SPVOLA
```

APPENDIX X. (continued)

```
      WRITE (LTRMO,*) 'MASS FLOW RATE=',DMASS
      WRITE (LTRMO,*) 'MASS FLOW RATE OF WATER=',DMCAIR
      WRITE (LTRMO,*) 'FUEL MOISTURE CONTENT=',FUELMC
      WRITE (LTRMO,*) 'EFFECTIVE FUEL HEAT CONTENT=',HCEFF
      WRITE (LTRMO,*) 'ENTHALPY=',H
      WRITE (LTRMO,*) 'HEAT FLOW RATE=',DH
C
C: Turn control over to SLAM.
C
      CALL SLAM
C
      STOP
      END
```

Subroutine STATE: BIO3STATE:FOR

```
C
      SUBROUTINE STATE
C
      INCLUDE BIO3COM1:FOR
      INCLUDE BIO2COM1:FOR
      INCLUDE SCOM1:FOR
C
      EQUIVALENCE (DFUELBURN,SS(1)),(DMCDA,SS(2)),(DHDA,SS(3))
     1,(FUELBURN,SS(4)),(TDBDA,XX(6)),(RHDA,XX(7))
      EQUIVALENCE (DRYPOT,XX(8))
C
C: Level equations:
C
      DFUELBURN = DFUELBURN+DDFUELBURN*DTNOW
      DMCDA = DMCAIR+DWATER
      DHDA = DH+DBTU
      FUELBURN = FUELBURN+DFUELBURN*DTNOW
C
C: Auxiliary equations:
C
      TR = (TDBDASET-TDBDA)/TDLY
      HDA = DHDA/DMASS
      HMCDA = DMCDA/DMASS
      TDBDA = (HDA-1061*HMCDA)/(0.2405+0.444*HMCDA)
      TABSDA = TDBDA+459.69
      PVDA = HMCDA*14.696/(0.62198+HMCDA)
      PSDA = EXP(54.6329-12301.688/TABSDA-5.16923*ALOG(TABSDA))
      RHDA = PVDA/PSDA
      DBTUTEM = HCEFF*DFUELBURN*60/1000000
      EFF = TABLI(EFFVAL,BTUVAL,DBTUTEM,NEFFVAL)
      HMCSAT = 0.62198*(PSDA/(14.696-PSDA))
      DRYPOT = (HMCSAT-HMCDA)*DMASS
C
```

APPENDIX X. (continued)

```
C: Rate equations:
C
      DDFUELBURN = TR*DMASS*0.2405/HCEFF
      DWATER = FUELMC*DFUELBURN+(1-FUELMC)*DFUELBURN*0.56
      DBTU = HCEFF*DFUELBURN*EFF
C
C
      RETURN
      END
```

Sample SLAM data file: BIO3SLAM:DAT

```
GEN,LITTLE,SENSITIVITY,3/3/84,1.;
CONTINUOUS,0,4,1.,1.,1.;
RECORD,TNOW,TIME,10,B,1.;
VAR,XX(6),T,DRYING  TEMP.,MIN(10.),MAX(10.);
VAR,XX(7),H,RELATIVEHUMIDITY,MIN(.1),MAX(1.);
VAR,XX(8),P,DRYING POTENTIAL,MIN(10.),MAX(10.);
RECORD,TNOW,TIME,11,T,1.;
VAR,SS(4),F,FUELUSE,MIN(10.),MAX(10.);
INITIALIZE,1,60;
INTLC,XX(6)=60.,XX(7)=.3;
INTLC,SS(1)=0.,SS(2)=0.,SS(3)=1.,SS(4)=0.;
FIN;
```

Common variable file: BIO2COM1:FOR

```
      COMMON /BIOCOM1/ DDFUELBURN,DMCAIR,DWATER,DH,DBTU,TR
     1,HDA,DMASS,HMCDA,TABSDA,PVDA,PSDA,HCEFF,TABS,PS,PV,RWV
     2,HMCAIR,SPVOLA,LTRMI,LTRMO,TDB,RH,DAIR,TDBDASET,TDLY,H
     3,FUELMC,FUELHC,EFFVAL(5),BTUVAL(5),NEFFVAL,EFF
C
      DATA LTRMI,LTRMO /105,108/
```

Common variable file: BIO3COM1:FOR

```
      COMMON /BIOCON2/ HMCSAT
```

Input values data file: BIO3CON1:DAT

```
60.,.3,15000.,130.,12.,.33,7200.
```

MSU

COLLEGE OF AGRICULTURE

MONTANA STATE UNIVERSITY
AGRICULTURAL EXPERIMENT STATION
SOUTHERN AGRICULTURAL RESEARCH CENTER
RTE 1, BOX 131
HUNTLEY MT 59037

RECEIVED
OCT 17 1984
MONT. DEPT. of NATURAL RESOURCES & CONSERVATION

October 16, 1984

Mr. Howard Haines
Department of Natural Resources
and Conservation
Energy Division
32 South Ewing
Helena, MT 59620

Re: Documentation for Milestone 17, DNRC Project RAE-83-1025, Southern Agricultural Research Center, Huntley, MT 59037

Howard, I will send a copy of loose page thesis under separate cover. In reply to your comments:

pp 37 refers only to biofuels transportation from storage area to burner (I'm not sure if the page number is correct).

pp 31 Table 1 total BTU/Ac you're right should be 4.79×10^6.

pp 59 We did replace the ceramic filter with a stainless steel filter, which was supplied at no cost from the company. This unit worked much better.

pp 65 Thank you for giving us that information, and will check with those people.

Budget Expenditures:

Enclosed is the monies expenditure which were actually spent to initiate, set up, operate and analyze the total system. Not included in the budget sheet is the time spent by myself and the farm crew in administration and field activities for all grain corn production and handling.

Gilbert F. Stallknecht
Superintendent
Southern Ag. Research Center
748 Railroad Highway
Huntley, MT 59037

GFS/jas

TELEPHONE (406) 348 3400

October 16, 1984

SUMMARY FOR DNRC PROJECT
Southern Research Center

Amount Authorized		$ 46,000.00
Salaries	$ 17,255.04	
Benefits	725.47	
Supplies	13,004.29	
Travel	296.99	
Capital	19,186.24	
Awards	286.60	
Indirect Charges	4,480.37	
TOTAL	$ 55,235.00	55,235.00
		- $ 9,235.00

DNRC - 26000 337
Southern Research Center
Huntley, MT 59037

LISTING OF EXPENDITURES

	Salary	Benefit	Supplies	Travel	Capital
Little, Mark (Mar-May)	2,400.00				
Little, Mark - June	800.00				
Benefits (mar-May)		45.60			
Work Comp, June		15.88			
Campus Store			1.74		
Little, Mark (July)	800.00				
Work Comp, July		15.88			
Billings Machine Shop			33.99		
Little, Mark				136.40	
Wodrich, Timothy				118.30	
Pacific Hide & Fur			42.19		
Little, Mark - Aug	800.00				
Balzer, Terral	152.00				
Grusing, Steven	256.00				
Benefits (Aug)		54.38			
Mid Valley Lumber			24.69		
Sterling Reprographics			2.50		
Worden Ready Mix			1,335.25		
Stockroom Sales			38.30		
A-L Welding Products			35.00		
Graybar			27.00		
Sterling Reprographics			6.09		
Kaspers			13.10		
Peavey Co.			7.01		
Sukup Mfg. Co.					977.00
Sukup Mfg. Co.					1,950.00
Sukup Mfg. Co.					6,090.00
Project Freight Line					548.25
Little, Mark	800.00				
Balzer, Terral	760.00				
Grusing, Steven	288.00				
Benefits (Sept)		114.80			
Little, Mark				10.50	
Little, (communications)				25.29	
Little, reimburse			1.59		
Project Freight			708.68		
Pacific Hide & Fur			60.59		
Yellowstone Co. Imp.			12.14		
Graybar			92.07		
Mid Valley Lumber			249.60		
Bearing Supply			4.79		
Power Transmission Equip			37.58		
Weissman & Son			4.16		
Graybar			16.20		
Landmark Homes			80.00		

	Salary	Benefit	Supplies	Travel	Capital
Worden Ready Mix			98.00		
Safeway Supply			135.00		
Damjanovich Construction			960.00*		
Triangle Irrigation					
G.D. Eastlick					2,121.00
Behlen Mfg. Co.					1,500.00
Little, Mark	800.00				5,999.99
Balzer, Terral	266.04				
Benefits (Oct)		39.95			
Erickson, Lee				6.50	
Worden Ready Mix			784.00		
General Electric Co.			539.28		
Graybar			1,848.90		
Little, reimburse			25.46		
Power Transmission			25.34		
General Electric			206.13		
Art-Photo Sales			56.00		
Graybar Electric			72.48		
Jacobs Electric			1,375.00*		
Damjanovich Construction			226.61*		
Little, Mark (Nov)	800.00				
Benefits (Nov)		16.61			
General Electric			399.98		
Art-Photo Sales			13.51		
Little, Mark (Dec)	800.00				
Benefits		15.88			
Little, Mark (Jan)	800.00				
Benefits (Jan)		15.88			
Little, Mark (Feb)	800.00				
Benefits (Feb)		15.88			
Technical Services			65.74		
Art-Photo Sales			21.06		
Little, Mark (Mar)	800.00				
Benefits		15.88			
Art-Photo Sales			7.02		
Little, Mark (Apr)	800.00				
Benefits		15.88			
Little, Mark (May-June)	1,600.00				
Benefits (May-June)		30.14			
Beltram, Daniel (Sept)	176.00				
Martinez, ERic (Sept)	416.00				
Robertson, Brad (Sept)	416.00				
Benefits		100.00			
Beltram, Daniel (Oct)	653.00				
Martinez, ERic (Oct)	32.00				
Benefits		110.00			
Beltram, Daniel (Nov)	519.00				
Martinez (Nov)	64.00				
Martinez, Eric (Nov)	190.00				
Robertson, Brad (Nov)	267.00				
Jacobs Electric			589.86		
Graybar Electric			100.26		

	Salary	Benefit	Supplies	Travel	Capital
Jacobs Electric			175.00*		
Builders Supply			632.17		
Peavey			31.63		
Fisette, Gordon (Portion of concrete)			400.00		
General Electric			663.09		
Yellowstone Valley Electric			1,304.70		
TOTALS	17,255.04	725.47	13,004.29	296.99	19,186.24

* Labor portion of invoices.

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